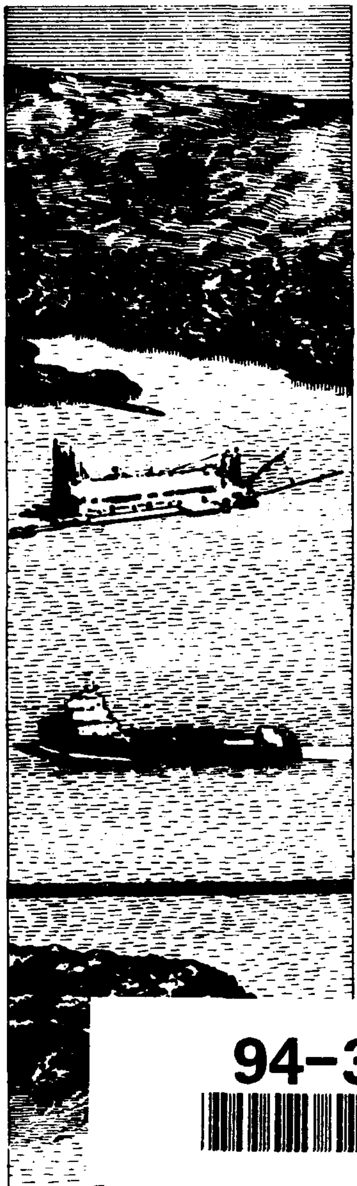
US Army Corps of Engineers



DREDGING RESEARCH PROGRAM

TECHNICAL REPORT DRP-94-5

IMPROVING SITE CHARACTERIZATION FOR ROCK DREDGING USING A DRILLING PARAMETER RECORDER AND THE POINT LOAD TEST

by

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September 1994

Final Report

Approved For Public Release; Distribution Is Unlimited

Prepared for DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit No. 32472

The Dredging Research Program (DRP) is a seven-year program of the US Army Corps of Engineers. DRP research is managed in these five technical areas:

Area 1 - Analysis of Dredged Material Placed in Open Waters

Area 2 - Material Properties Related to Navigation and Dredging

Area 3 - Dredge Plant Equipment and Systems Processes

Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems

Area 5 - Management of Dredging Projects

US Army Corps of Engineers
Waterways Experiment Station

Dredging Research Program Report Summary

Improving Site Characterization for Rock Dredging Using a Drilling Parameter Recorder and the Point Load Test (TR DRP-94-5)

ISSUE: Characterization of rock dredging sites is a critical issue as evidenced by frequent and large differing site condition claims with attendant problems in planning and estimating such work. Most of these problems have been associated with mechanical (nonblasting) excavation which necessarily involves weak and variable rock formations. Use of mechanical rock dredging is increasing and often it is done with equipment operating near the limit of capability as it relates to the strength of rock being excavated. A need existed to enhance what may be learned from traditional rock borings such that both vertical and areal site coverage could be increased. Also, since only a small part of all rock core recovered in exploration could be economically tested, a low-cost field strength index, which could be correlated with traditional strength parameters, was needed to provide additional coverage of highly variable coastal deposits and to monitor dredged material strengths.

RESEARCH: The approach to the work was to test and further develop two existing technologies; First, the concept of instrumenting an exploration drill rig and relating its operational parameters (such as bit pressure, rotation rate, advance rate, etc.) to characteristics of the rock being drilled was investigated. The applicability of such a system for drilling typical coastal deposits was to be investigated and demonstrated. Second, the point load test for rock was investigated. This test method had produced a proven field strength index for hard rock, which could be correlated with unconfined compressive strength. A comparative testing program was conducted to demonstrate the usefulness of the point load index test to obtain a field strength index for dredging.

SUMMARY: An instrumented drilling system was investigated as to capabiity and refined as to operational techniques and methods of correlating drilling parameters with in situ material properties. The system was used at four dredging sites. The point load test was shown applicable for materials typical of many coastal deposits. A correlation of the point load index with unconfined compressive strength was demonstrated for several dredging sites and for other weak and/or saturated rock selected for uniformity. Correlation factors for these weak materials were found to be much lower than for hard rock applications. Recommended testing procedures were developed.

AVAILABILITY OF REPORT: The report is available through the Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, telephone number (601) 634-2355. National Technical Information Service (NTIS) report numbers may be requested from WES Librarians.

To purchase a copy of the report, call NTIS at (703) 487-4780.

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Dredging Research Program

Technical Report DRP-94-5
September 1994

Improving Site Characterization for Rock Dredging Using a Drilling Parameter Recorder and the Point Load Test

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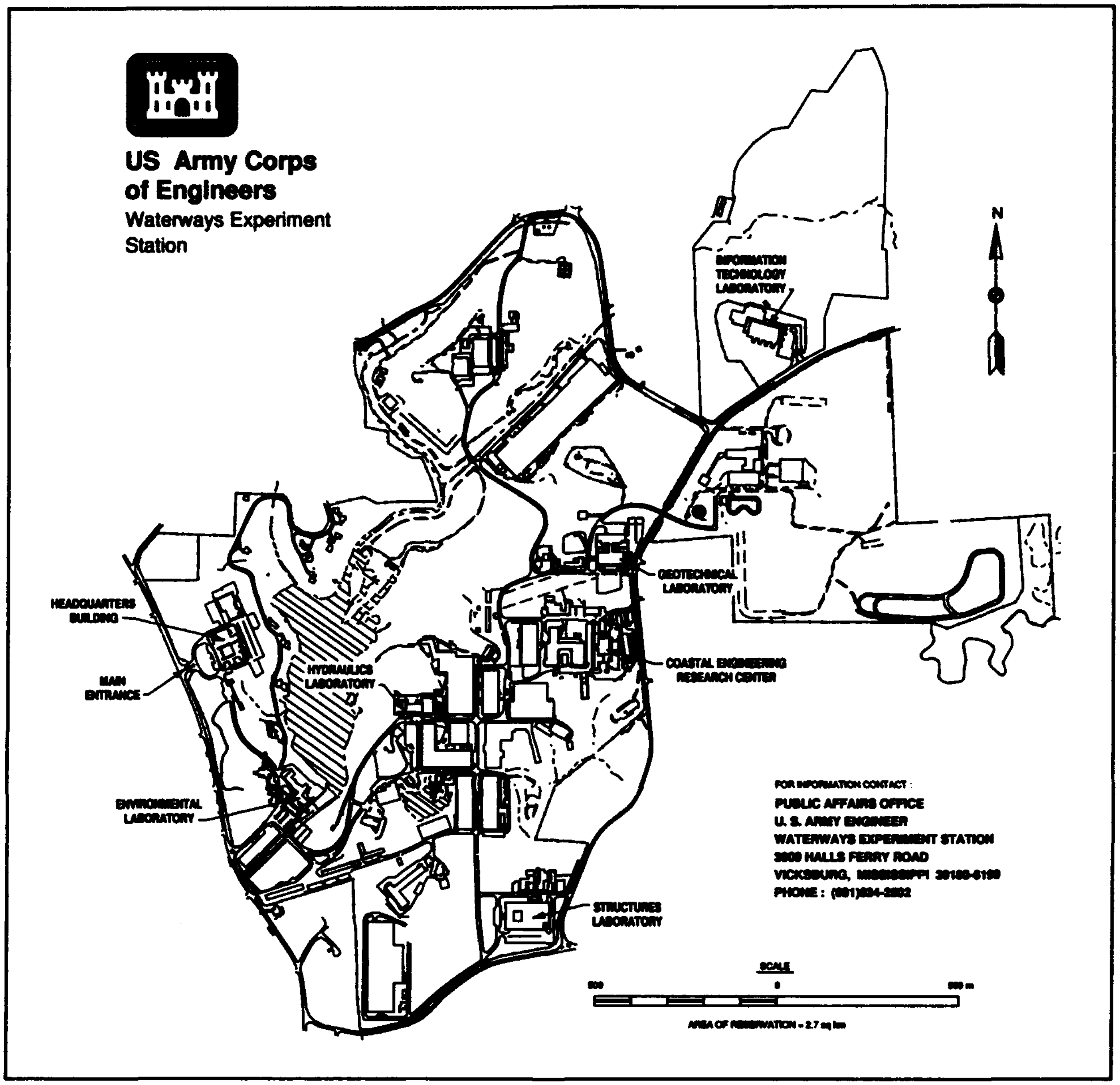

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Preface

The work described in this report was authorized as part of the Dredging Research Program (DRP) by Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Work Unit 32472, "Descriptors for Rock Material to be Dredged." The HQUSACE Chief Advisors for the DRP were Messrs. Bob Campbell and Barry W. Holliday. Mr. Henry R. Schorr, U.S. Army Engineer District, New Orleans, and Mr. Timothy Pope, U.S. Army Engineer Division, South Atlantic, served as Chief Technical Monitors for DRP Technical Area 2. Dr. Don C. Banks, Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES), was the Technical Area Manager. Mr. E. Clark McNair, Jr., Coastal Engineering Research Center (CERC), WES, was DRP Program Manager. Dr. Lyndell Z. Hales, CERC, WES, was the DRP Assistant Program Manager. Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., were Director and Assistant Director, respectively, of CERC, which oversees the DRP.

The work was conducted under the general supervision of Dr. William F. Marcuson III, Director, GL. Mr. Hardy J. Smith, Rock Mechanics Branch (RMB), Soil and Rock Mechanics Division (SRMD), GL, was Principal Investigator and author of this report. Mr. Smith worked under the direct supervision of Dr. Don C. Banks, Chief, SRMD, GL, and Mr. Jerry S. Huie, Chief, RMB, SRMD.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. COL Bruce K. Howard, EN, was Commander.

For further information on this report or on the Dredging Research Program, contact Mr. E. Clark McNair, Jr., DRP Program Manager, at (601) 634-2070.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.017453	radians
feet	0.3048	meters
foot-pounds (force)	1.355818	meter-newtons or joules
inches	25.4	millimeters
feet per minute	0.005080	meters per second
pounds (force)	4.448222	newtons
pound inches per cubic inch	0.006895	megajoules per cubic meter
pounds per square inch	6.89	kilopascals

1 Introduction

Background

Site characterization is of special concern when rock is to be dredged by mechanical (non-blasting) excavation. Dredging of rock by mechanical means involves the use of equipment with limited capabilities with respect to rock strength and rock mass structure. In contrast, when higher strength rock is encountered in drill and blast dredging, additional explosive or more shot holes may be required but usually the same equipment can be used as was mobilized for the less difficult operation. Even so, a general trend toward the use of mechanical excavation equipment in increasingly difficult materials is seen in mining, tunneling, dredging, and open excavations (Bennett et al. 1985, Hignett 1984, Caterpillar Inc. 1986). As larger and more powerful machines have become available their use as an alternative to drilling and blasting has been pushed by both economic considerations and a desire to avoid blasting in developed or populated areas. The rock dredging projects of the U.S. Army Corps of Engineers (USACE) have followed this trend. USACE dredging projects are now typically excavated by contract, and in recent years the USACE has experienced numerous differing site condition claims on rock projects. Several example claim situations were outlined in the U.S. Army Engineer Waterways Experiment Station (WES) report entitled "Future Research Needs for the Dredgeability of Rock" (Smith 1986). Since this report, several additional rock dredging claims have been settled. Such claims are typically large, usually in the millions of dollars and sometimes more than double the original bid cost. These differing site condition claims are commonly based on the contention that rock encountered is harder to dredge with available equipment than the contractor had inferred from bidding documents. Such claims necessarily hinge on either the characterization of the rock material or the predicted performance of particular dredging equipment in excavating such material, the two being interrelated. Many of the harbors and river channels where the Corps is involved in planning and contracting rock dredging now have areas of rock bottom. As harbor development continues, more rock will certainly be encountered with each successive deepening. Much of this material will be mechanically dredged. Rock masses that can be dredged using mechanical methods are necessarily weaker and are usually highly variable in strength and rock mass structure.

Dredging contractors' claims on mechanical dredging operations are often based on material strength changes, so that both the determination of rock strengths during site exploration and the monitoring of dredged material strengths during dredging operations are critical in the typically weak, highly variable rock formations. Both the intact strength and structural characterization of all rock at a dredging site are necessarily inferred from testing selected core from a few borings and review of the boring logs. Representative sampling using traditional exploration and testing is limited by available funds. A need clearly exists to enhance what may be learned from, and to reduce the cost of, traditional rock borings such that both areal and vertical site coverage is increased. Since only a small part of all rock core recovered in exploration can be economically tested, a low-cost field strength index, which could be correlated with traditional strength parameters, is needed to provide additional coverage of highly variable coastal deposits and to monitor dredged material.

Purpose and Scope

The statement of objective for the work unit was to "determine functional geotechnical descriptors for rock masses applicable to underwater excavation" and to "reduce costs and improve effectiveness of exploration for determination of rock dredgeability." The word "functional" indicated that simply a unique description of the rock or rock mass, such as a good geologic description, was not sought, but that those parameters would be identified which influenced the engineering assessment of underwater excavation of rock. A large-scale parametric study was first considered to evaluate the relative influence of rock mass parameters (intact rock strength, joint spacing, interbedding, and structural orientation relative to excavator geometry) on underwater excavation. Earlier work had shown which rock mass parameters would likely influence mechanical excavation based on an extrapolation from dry excavation technology (Smith 1987). Earlier work had also shown that the same rock will likely be weaker under water than when encountered in the more usual surface excavations, because both unconfined compressive strength of intact rock (Vutukuri, Lama and Saluja 1974) and joint strength (Bieniawski 1974) are less for saturated conditions. Additionally, because dredges excavate rock from a floating plant, the high reactive forces and excavation geometry common in tunneling and mining equipment are not available for comparison. Thus predictive systems developed from surface excavation data cannot reasonably be converted for dredging use, and the large-scale study of relative parameter influences was necessary if a predictive system for underwater excavation was to be developed. However, such a parametric study would require developing a large, unprecedented test facility. Because of the high cost and organizational constraints involved in the large-scale study, and since the parameters influencing rock dredging were known (although their relative influence is unknown), the Dredging Research Program (DRP) Field Review Team directed the work away from a predictive system for dredgeability and the entire emphasis was placed on site characterization. Both the DRP Field Review Team and the author still saw intact rock strength and rock mass structure such as joints, interbedding with weaker deposits, and structural

orientation as important factors to consider. The approach to the work was to test and further develop two existing technologies: First, the concept of instrumenting an exploration drill rig and relating its operational parameters (such as bit pressure, rotation rate, advance rate, etc.) to characteristics of the rock being drilled had been demonstrated by others in nondredging applications. The applicability of such a system to subaqueous operations for drilling typical coastal deposits was to be investigated and demonstrated. Second, the point load test for rock core and hand samples had produced a proven field strength index for hard rock which could be correlated with unconfined compressive strength. A comparative testing program was to be conducted to demonstrate the possible usefulness of the point load index test to obtain a field strength index for weak, saturated rock.

2 A Drilling Parameter Recorder for Rock Dredging Exploration

DPR Introduction

Dredging applications have been developed for a new technology that significantly enhances what can be learned from traditional subsurface rock borings. The basic system, involving proven concepts and applications for land surface use, has now been demonstrated in subaqueous applications at several dredging sites. The interpretive techniques that have been further developed involve both site-specific correlations and calculated combined-parameter estimates of in situ conditions, such as estimates of unconfined compressive strength and specific energy of drilling. A hydraulic drill rig was instrumented to record its behavior during drilling operations. The nature of subsurface geological materials can be inferred from various drilling parameters such as bit pressure, speed of rotation, instantaneous advance rate, etc. The drilling parameter recorder (DPR) is a generic name for systems used to record the operating characteristics of a drill rig. Devices ranging from paper chart recorders to computerized systems for monitoring drilling production rates and efficiencies are commercially available, but virtually all of them record data relative to elapsed time. For site characterization work, the data record must be in direct correspondence to position in the bore hole. This is the primary reason for selection of an Enpasol recorder and related software (Girard et. al. 1986) for this DPR system. For the purpose of this report, "DPR" refers to the WES- modified DPR system using the Enpasol recorder and software by Solentanche. The DPR system described here is the first of its kind to be used in the United States.

Need and Method of Application

In planning and estimating for rock dredging and in resolving differing site condition disputes, a knowledge of intact rock strength and rock mass structure, as well as the vertical and areal extent of rock is needed. Typically, less is known of subsurface conditions for rock dredging than for other construction because the

rock to be dredged is usually less accessible. Limited bottom borings are often the only indicator of rock conditions. Even surface outcrops of otherwise exposed rock are under water, but most outcrop rock is also under obscuring shoaled material. Rock borings over water involve high costs. For subaqueous drilling, a drilling platform must be provided and the mobilization and daily costs for this platform can easily exceed all other costs combined: i.e. costs of drilling equipment and supplies and cost for the drill crew. Also, cored boreholes over water must be cased from above the water surface into the bottom before coring operations can begin. In site explorations for rock dredging, the current practice is to core all boreholes and give results of boring logs at selected locations; geologic description and/or unconfined compressive strength (UCS) of selected pieces of core are frequently given. Present assessments of subaqueous rock conditions can be inadequate because:

a. Frequently, only a small number of borings are available because cored borings taken over water are expensive.

b. Core recovery is often poor in the coastal deposits typically excavated by mechanical dredges because the rock is weak and the coring process breaks it.

c. Engineering properties other than UCS, which is commonly the only data given other than a general geologic description, can influence excavatability.

d. Although a good geologic description serves to identify the material, it does not directly relate to engineering properties.

Available methods of application for the DPR system, which were used at DPR dredging sites (given below under "DPR Setup and Field Use"), have included DPR use in a similar way to that of various remote sensing technologies, in which data are taken by remote sensing at many locations over a site and direct data based on examination of physical samples from a few locations are used to interpret the larger body of data. In noncoring drilling operations over water, boring using a tri-cone roller bit can produce a DPR record without the need for setting casing and can attain a much faster drilling rate than coring operations. In order to save field production time in drilling and logging operations as well as laboratory testing costs for a given number of holes, most holes can be drilled with a roller bit and the recorded drilling parameters can be correlated with a small number of cored holes, usually paired with roller bit holes, produced without moving the drilling platform. Such a site-specific correlation method is especially important where conditions are highly variable and a large number of boreholes are needed to obtain adequate site coverage.

In using the above-described method some cored holes are necessary and certainly all holes will be routinely cored at some sites. In these cases where holes are cored, and if the DPR is also employed, geologic contact elevations can be determined accurately even where core recovery is poor. Even in zones where no

core recovery is possible, the DPR provides a continuous record of drilling parameters which are related to in situ material properties. Hard and soft zones can be identified and the location of recovered core pieces within a drill run can usually be identified with certainty. When core recovery is poor, the location of core within the core run is especially critical where a large intact rock core zone occurs near project depth. If the corresponding zone of continuous rock is above project depth, it must be dredged. Assuming the location of core at the bottom of the core run, which is a common logging practice in the absence of other evidence, could easily produce an erroneous record.

Description of the DPR

The DPR is a data acquisition system that monitors, measures, and records various physical values called drilling parameters that reflect the operation of the drill rig, thereby producing a record of the characteristics of the formation being drilled. The following eight parameters can be measured, quantified, and recorded on an analog graphical plotter (Figure 1) and digitally recorded on tape by a microcomputer integrated into the equipment:

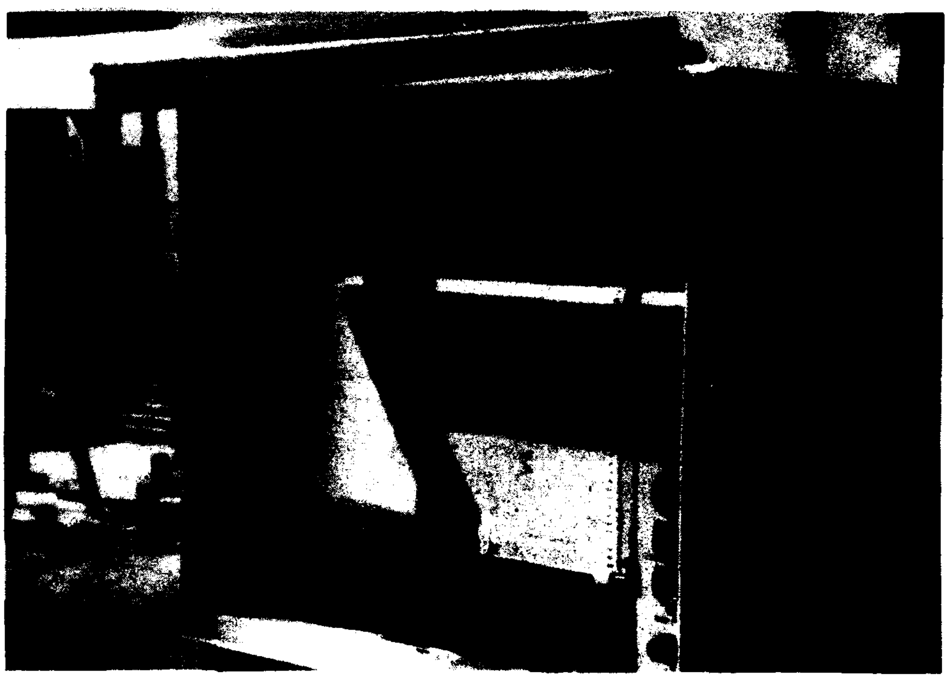

Figure 1. The DPR's housing with integral analog plotter where any four of the parameters being recorded can be viewed as selected by operator

a. Drilling fluid pressure.

b. Relative torque indicated by pressure to hydraulic motor for the drill string.

c. Downthrust on the drill bit.

d. Rate of advance or penetration speed.

e. Rotation rate.

f. Holdback pressure on drill string.

g. Reflected vibrations (accelerations).

h. Time to drill one digitized increment of depth.

Additionally, accumulated depth of the bit and number of rods in the drill string are recorded, and manual input provides a record of the date, site, boring designation, and the drill rod and bit type. The reflected vibrations parameter, intended for percussive drilling methods, was not used in this study. Also, drilling fluid pressure, particularly useful in grouting work, was not monitored.

A software program allows the user to select numerical parameters, plotted parameters, and other pertinent information related to the borehole being drilled. Also, the program organizes the storage of the data on tape (i.e., finds available space, records the data, detects the end of tape, etc.) for later office analysis. The computer portion of the DPR is also equipped with a self test that detects errors, and where possible, identifies and localizes these problems.

The entire system is interfaced with a drill rig through various sensors that relate physical parameters of the rig and parameters to be recorded. These sensors include a cluster of pressure transducers, a movement transmitter, and an electromagnetic proximity detector. Pressure transducers (Figure 2) are connected to the hydraulics of the drill rig and convey drilling fluid pressure, relative torque, downthrust pressure, and holdback pressure of the drill rig to the DPR. A movement transmitter, located at the top of the drilling mast and connected to the rotation head by a cable, provides the feed speed or advance rate. Measurement of the rotation speed is provided by the electromagnetic proximity detector attached to the rotation head of the drill rig. All transducer data are fed back to the DPR via reinforced electrical cables so that no telemetry is used. The entire system has proven highly reliable under rough use in saltwater environments.

Figure 2. Close-up of pressure transducers showing DPR transducer housing for sensing drilling fluid pressure, pressure to hydraulic drive motor, downthrust and holdback pressures

DPR Setup and Field Use

Initially designed for construction exploration, the Enpasol DPR had been previously used in Europe on underground construction projects such as the English Channel Tunnel and on numerous grouting projects. The most critical task of the present research was to assess the use of DPR systems in rock exploration for dredging applications. All DPR explorations were accomplished using the same drill rig and instrumentation. The DPR system was installed at WES on a Longyear HC 150 palletized hydraulic drill rig. Installation required calibration setup in the Enpasol software. Based on desires of field personnel, the basic or directly measured drilling parameters were programmed to read in non-SI

(English) units, so that all pressures read in pounds per square inch (psi), rotations in hertz (H_z) and time in seconds. Computed parameters were similarly programmed into the software, such as bit force, which was expressed as pounds force (lbf). Programming of bit force was necessarily specific to the drill rig as downthrust and holdback pressures must be multiplied by their respective piston areas to obtain the difference of downthrust and holdback forces. That resultant force plus the weight of the rod and drill rig head were needed to program bit force.

After initial field use, an additional drill rig-specific calibration to obtain torque was accomplished (see "Specific Energy of Drilling", page 16); however, this made no change in field operation where pressure to the hydraulic drive motor was still an indicator of relative torque, and the addition to the software allowed analysis of previously obtained field data to determine true torque. The DPR was first used for subaqueous drilling in New York Harbor in December of 1988 and was subsequently used in explorations at Grays Harbor, Washington, Wilmington Harbor, North Carolina, and Kings Bay, Georgia (see Figure 3).

Figure 3. DPR exploration using the jack-up barge, Explorer, at Kings Bay, Georgia. Similar floating plant was used at New York Harbor

DPR drilling exploration in the Kill Van Kull channel of New York Harbor was performed on a self-propelled jack-up barge, which was supplied by the New York District through contract. This floating plant was easy to position and provided a stable platform while drilling with ample space for operation.

The New York District provided a location survey using shore targets to determine the same locations used in the previous exploration in the channel. WES was asked to perform DPR instrumented exploration because the previous exploration had an unknown vertical error in survey and there were locations where top of rock was difficult to determine due to the complex geology. Drilling methods included coring using NQ wireline (1.775-in. core)[1], splitspoon and a 3-1/8-in. rotary tri-cone roller bit. Splitspoon and rock coring were supported by the use of 4-in. casing drilled using a diamond bit. Unlike other sites, a variety of materials were encountered including glacial till, sandstone, and diabase, as well as overlying sediment material, which was sampled only in this exploration.

Rock core and splitspoon sampling were done for each new geologic condition. Once the geology was confirmed on the DPR field records, exploration drilling was continued using only the roller bit and the DPR. In some cases where only one hole was bored, the roller bit was used first; then after contact was made with the hard bedrock, a diamond coring bit was used, primarily because it could more readily cut the material, but this also provided additional core to the New York District.

The DPR record for WES Borehole No. 19 (New York District No. KC-35) provides an example showing the ease with which rock mass conditions are inferred from the basic drilling parameters (see Figure 4). This record shows the directly observed parameters usually monitored in the field on the strip chart recorder, although these data were digitized by the software and later displayed. This hole was first drilled to a depth of 5.6 ft with a roller bit. A field interpretation of the DPR record by Allen Kimbrell, WES, and Michael Fedosh, geologist, New York District, located the glacial till contact with diabase bedrock at 4.8 ft. The break is easily interpreted. Note that both torque and advance rate or speed are erratic as drilling proceeds through the glacial till. Then the advance rate, or speed, drops to near zero as the hard diabase is encountered, torque goes off scale and holdback pressure abruptly drops, indicating the rapid bit pressure increase. The borehole was completed using NQ wireline coring. Other examples of DPR records are given in the next section ("Interpreting DPR Results and Graphic Displays"). Methods of application and equipment for DPR exploration were the same at other field sites except as indicated below.

Exploration at Grays Harbor, WA, was performed using an anchor barge and tending tug furnished under contract by Quigg Brothers, Aberdeen, WA. The Seattle District supplied a survey boat and crew for borehole location and chose locations where a site survey had shown high bottom (presumed rock) left after earlier dredging using a suction cutter dredge. Drilling and sampling procedures were to attempt a coring run and a roller bit run wherever rock was encountered. A number of holes were abandoned when advancing the hole by washing down the drill string indicated no rock from the top of the bottom to the project depth. In addition, several holes were located over glacial till cobble; as drilling this

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page ix.

material was of no interest to the District, drilling at these locations was aborted. Operational problems with drilling were experienced, especially with casing, because of the high currents in this harbor; on one occasion, after 3 ft of coring, the barge had pulled off its anchors and had already drifted 4 ft before drilling was stopped to avoid breaking off of the drill string. Here, only 0.33 ft of the hard boulder-like rock was recovered and this material had clearly been redrilled several times, indicating vertical displacement of the barge during drilling. The material recovered for laboratory testing at this site was all a weak, silty sandstone. Wet core from this site could be easily molded underfoot and although classified geologically as rock, could have been tested as soil. Thirteen rock tests were performed on stronger, dry samples with a resulting unconfined compressive strength in the 300-psi range. DPR records had few anomalies in this weak rock, which had little structure such as joints or well-defined planes of weakness.

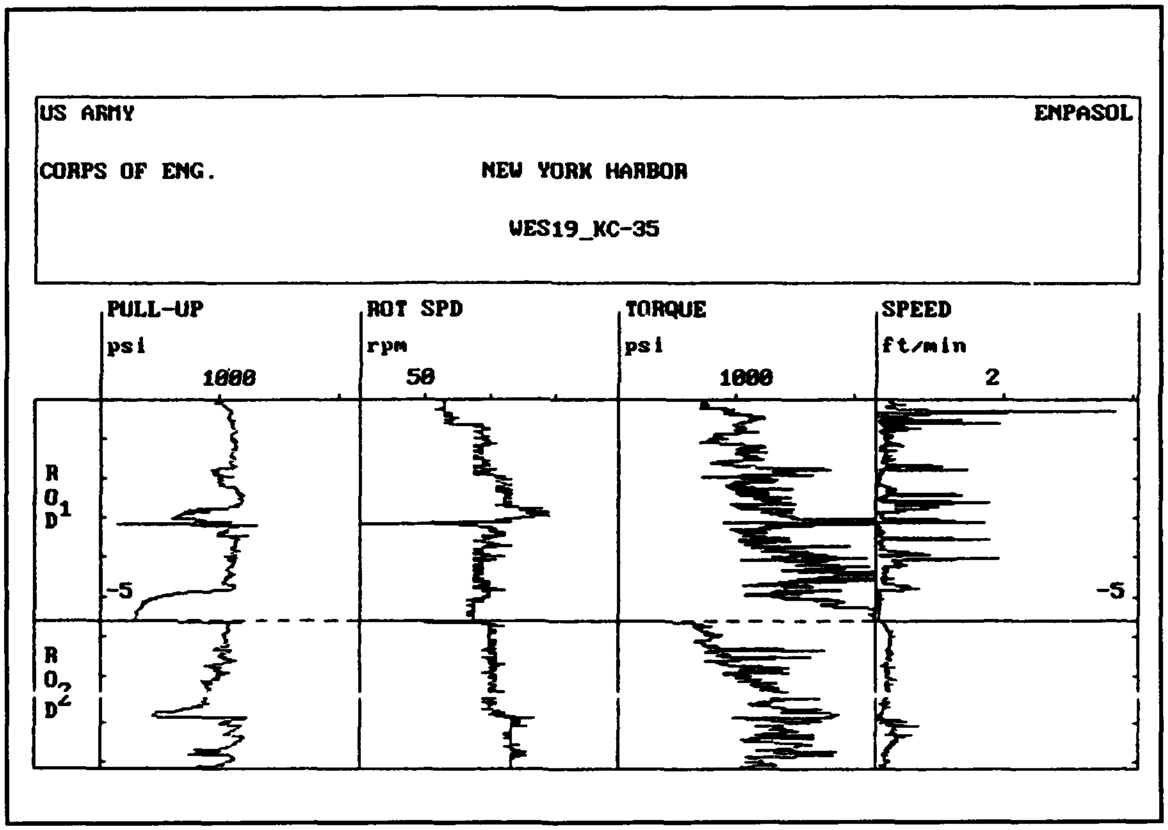

Figure 4. Basic observed parameters shown for WES Borehole No.19, New York Harbor

DPR explorations at Wilmington Harbor and at Kings Bay were in similar materials, classified as a biohermal lime rock. This rock was often vuggy, with shell casts, and sometimes had localized zones of weaker rock in the same core piece. Rock mass structure consisted of harder rock interbedded with zones of weaker rock or sand. DPR records of drilling in this type rock mass are used as examples of interpretive displays in the following section. Coring operations at these sites used a 4-in. core bit. This larger core size was primarily chosen to

increase the percent of core recovered, but this size core also provided sufficient cross section to obtain multiple smaller cores for the comparative testing program, which was conducted in support of the dredging use of the point load test, described in Chapter 3. The exploration at Wilmington Harbor was confined to the turning basin area, which was proposed for deepening. Drilling was performed from a spud barge positioned by a tending tug, both provided by Wilmington District. Survey of borehole locations was also provided by the District using land-based survey techniques. Although difficult to position, the spud barge was stable in the protected waters and good DPR records were obtained, even for bit force, which is the most sensitive parameter to vertical movement. The drilling at Kings Bay was accomplished using the jack-up barge Explorer and crew of the Savannah District. Positioning was provided by the barge captain using the onboard electronic positioning system and shore targets. The Explorer is similar to the jack-up barge used in New York Harbor and both provided excellent drilling platforms for DPR operations.

In the above explorations, a total of 87 rock boreholes were produced with corresponding DPR records. Under good field conditions successful DPR records were obtained using the spud barge and the anchor barge. However, the jack-up barges proved more convenient to position and, since the legs supported the barge out of water, concern was removed for the effects of small vertical movements on the DPR records, even in choppy open waters or near harbor traffic, producing wake.

Interpreting DPR Results and Graphic Displays

The DPR software produces graphic displays of any drilling parameter in the following alternative formats:

a. A continuous line against depth or "wireline" plot.

b. Three different block diagram displays against depth using fixed scale limits, statistical limits, or block names displayed as a function of block amplitude.

c. A histogram where data are not presented against the depth, but data of a particular parameter in a selected depth interval are statistically evaluated and results displayed as either cumulative or non-cumulative frequency of occurrence.

Figures 5 through 7 demonstrate several of the various DPR outputs. Data were obtained and interpreted for illustrative purposes from a single interval of a boring made at Wilmington Harbor, NC. The DPR can be used for all the sizes of core bits and roller bits for which the drill rig has capability. In this case, a 4- by 5.5-in., 10-ft core barrel was used. The recovered core was badly fragmented and eroded, with the largest fragment being about 0.8 ft long; approximately 70 percent of the core run was recovered.

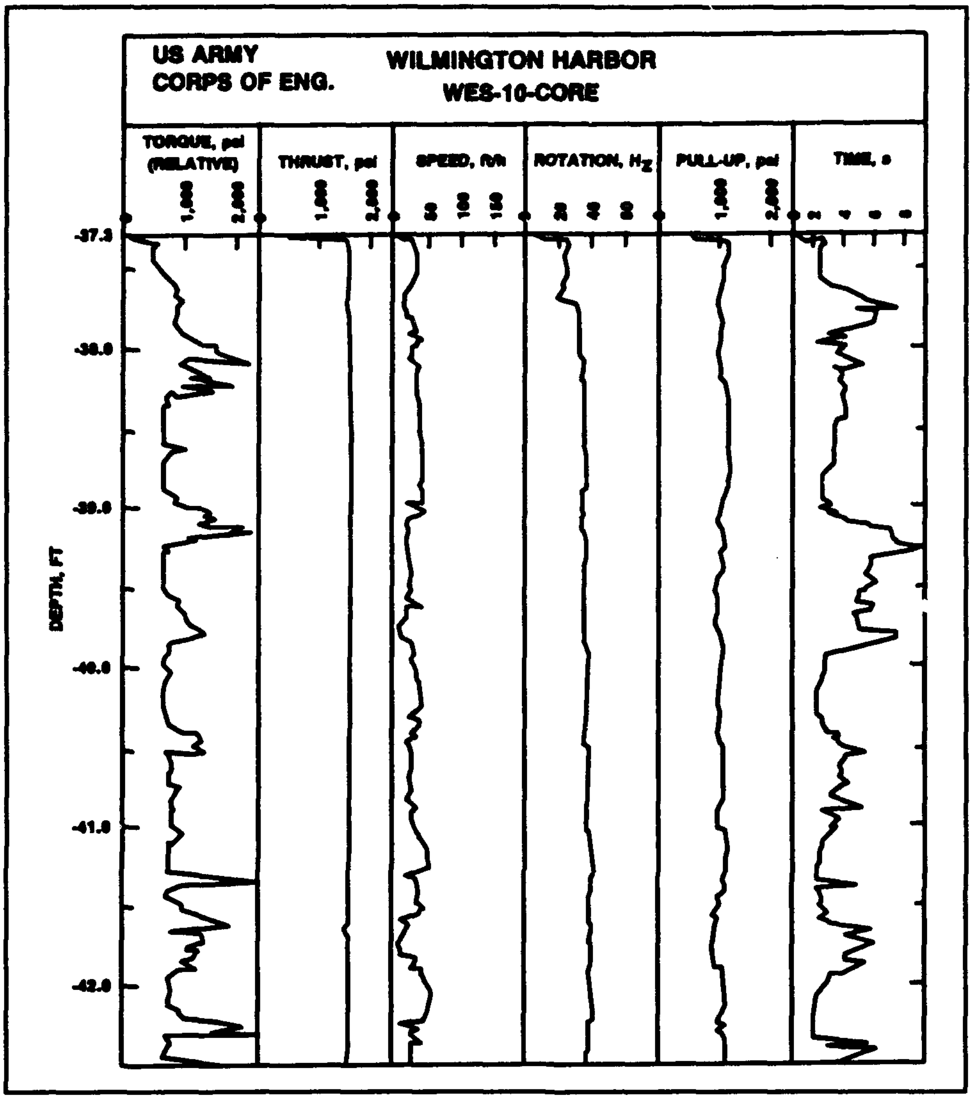

Figure 5. Directly measured drilling parameters

Figure 5 shows the graphical plots against depth of six directly measured drilling parameters using the wireline format. Depth is in feet beginning at the top of rod 1. The plot of TORQUE is the hydraulic pressure (psi) in the drill motor which is a direct indicator of relative torque. Note the responses of the pressure to variations in resistance to drilling. THRUST is the pressure in the forcing hydraulic cylinder, providing a downward force. It is relatively constant because design of the drill rig uses operator control of the PULL-UP or hold back cylinder to vary the force on the drill string. SPEED is the rate of advance of the bit while ROTATION depicts cyclic frequency of the rotation rate transducer and can be manipulated to produce revolutions per time, degrees per time, etc. The plotted parameter TIME is the number of seconds required for the drill bit to advance one depth increment of 5 mm; it is the inverse of SPEED and can be used as an advance rate measure in very hard rock. These directly measured parameters can

be refined in various ways and can also be used to procure computed drilling parameters against depth as discussed below. However, even these "raw" data have certain obvious correlations with material character. For example, if other parameters remained unchanged and relative TORQUE increased, a tougher and stronger material would be indicated. Similarly, an increase in rock strength would normally produce an increase in the plotted parameter TIME and a decrease in ROTATION and SPEED.

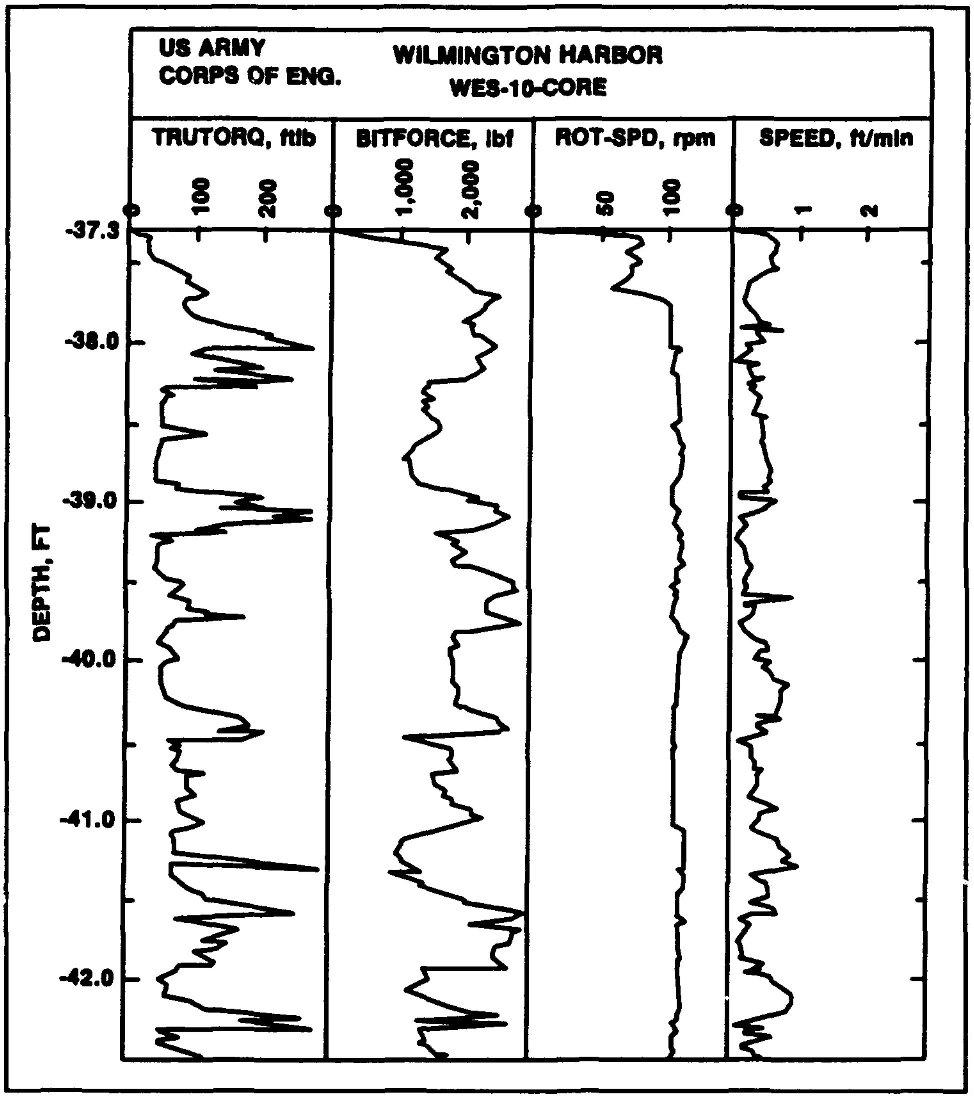

Figure 6. Calculated drill rig mechanical parameters from the raw data shown in Figure 5

Figure 6 shows calculated mechanical parameters describing the rig behavior during drilling the above-noted boring. The 'trutorq' parameter resulted from applying a correlation equation derived from torque versus pressure calibration

data. This calibration is described below in the section titled "Specific Energy of Drilling." The 'bitforce' parameter is the cumulative sum of directed forces and weights bearing on the bit. 'ROT SPD' is rotational speed of the drill string and bit recomputed to a meaningful unit. SPEED, or rate of advance, is displayed to a different scale.

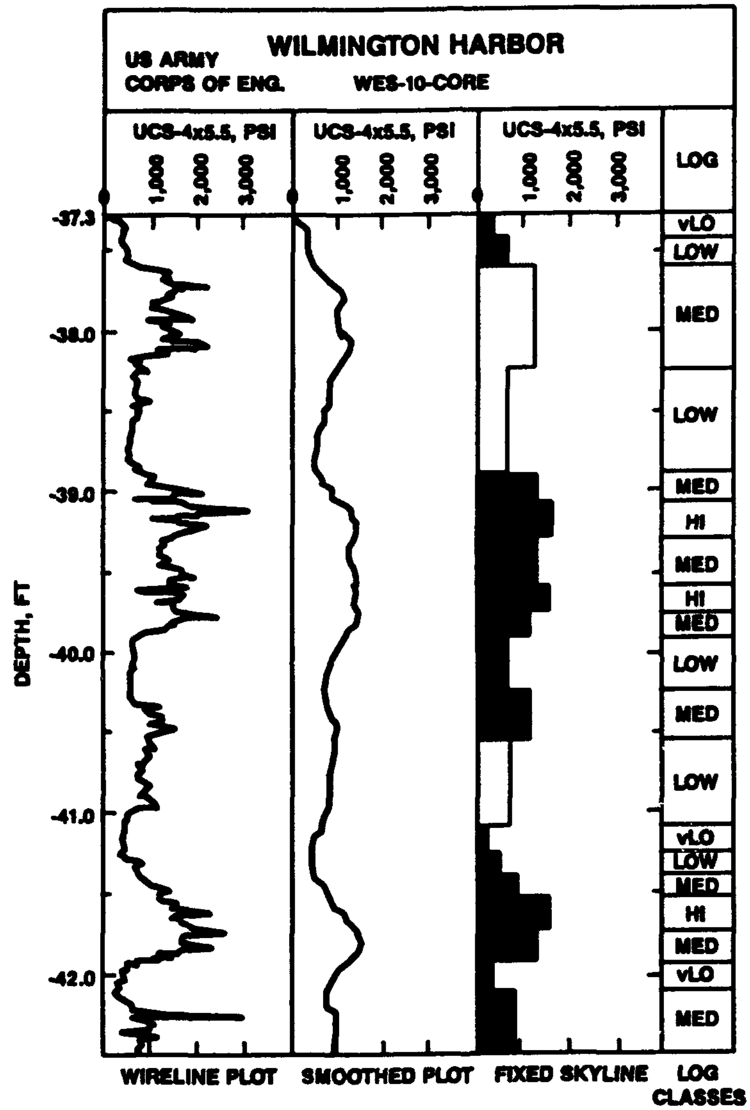

Figure 7. Four graphical forms of combined-parameter estimate of unconfined compressive strength from data shown in Figures 5 and 6

Figure 7 displays the same parameter in four different forms. A combined-parameter estimate of unconfined compressive strength is used here to illustrate these modes of display. The correlation of UCS with drilling parameters is discussed in a section below. The UCS parameter displayed here was computed

using data shown in Figure 6. The left-most column is a 'wireline' plot of the computed values while the second column is a smoothed version of the data. The plot is a running average of 10 data values (that is, averaged over 0.164 ft).

The third column is a 'skyline' or block representation using fixed proportions of full-scale values of the data. Minimum block height is, again, based on 10 data values or 0.164 ft of boring. The shading represents the variability of the values within single blocks, darker being more variable. The right-most (narrow) column provides a literal 'log' of the fixed-limit skyline plot in which the nomenclature refers to relative strength.

Specific Energy of Drilling

The specific energy of drilling (E_S) is the energy expended per unit volume of material removed by the drill bit or core barrel. E_S has been incorporated in the DPR as a computed drilling parameter. Because the DPR directly measures only a "relative" torque (pressure to the hydraulic drive motor) and torque was necessary to determine E_S, a torque versus pressure calibration equation was determined using a reaction disk and an in-line torque cell (see Figures 8 and 9). The resulting relationship was

$$T = 0.141 \ T_{rel} - 38.7 \tag{1}$$

where T = torque in foot-pounds
T_{rel} = "relative torque" in pounds per square inch

Although there was noticeable scatter in the data (postulated to arise from flexiblity in mechanical parts and in the hydraulic circuits), the correlation coefficient for this linear regression was 0.945 and indicates by its closeness to 1.0 that the correlation is valid. The standard deviation was 30.0 ft-lb which is only 3 percent at normal operating pressures in the 1,000-psi range. This result was significantly different from the theoretical linear relationship furnished by the drill rig manufacturer, which is a depiction of the hydraulic motor's design performance, given as:

$$T = 0.204 \ T_{rel} \tag{2}$$

This theoretical relationship gives higher values for torque at all operating pressures than does the empirical calibration. This calibration is specific to the drill rig so that use of any DPR system for recording pressures on other equipment would require a similar determination and modifying of the torque equation. Through the use of the modified software, all future and past parameter records obtained using this equipment can indicate E_S. The author opines that the specific energy expended by rock dredging equipment will correlate with E_S for at least the more massive rock materials. Such a correlation awaits actual dredging at sites where the DPR system has been used and will require funding of additional dredge instrumentation. This work, if accomplished, will postdate the Dredging Research Program. Figure 10 shows a "wireline" plot of E_S in two different units.

Figure 8. Setup to obtain actual calibration of torque from DPR pressures using torque cell and reaction disk

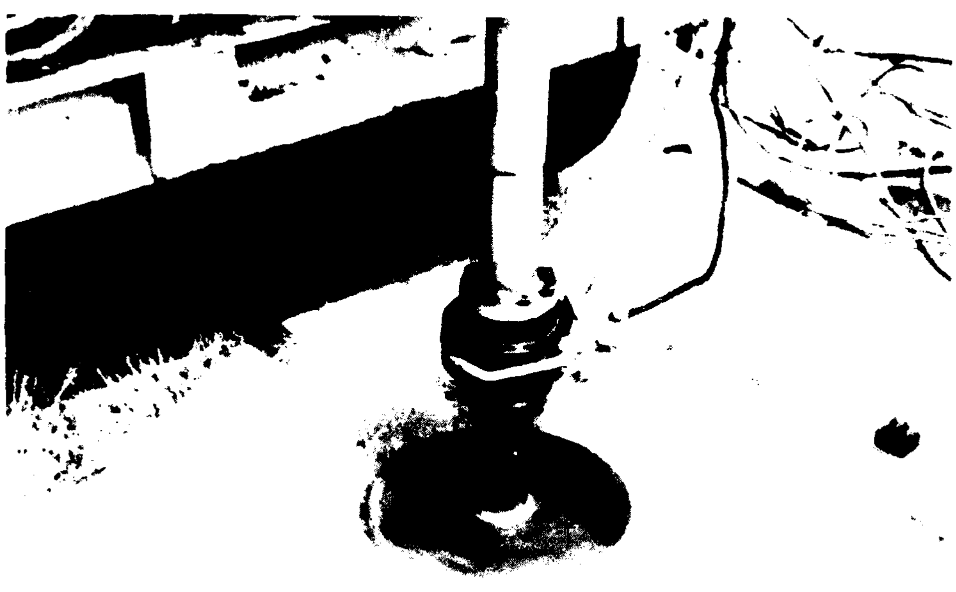

Figure 9. Close-up of torque cell and reaction disk

Here E_S is computed directly from known physical relationships with no empirical correlation involved. The software determines this parameter from known torque, speed of rotation, advance rate, bit force, and the cross-sectional area of material removed by the drill bit or core barrel.

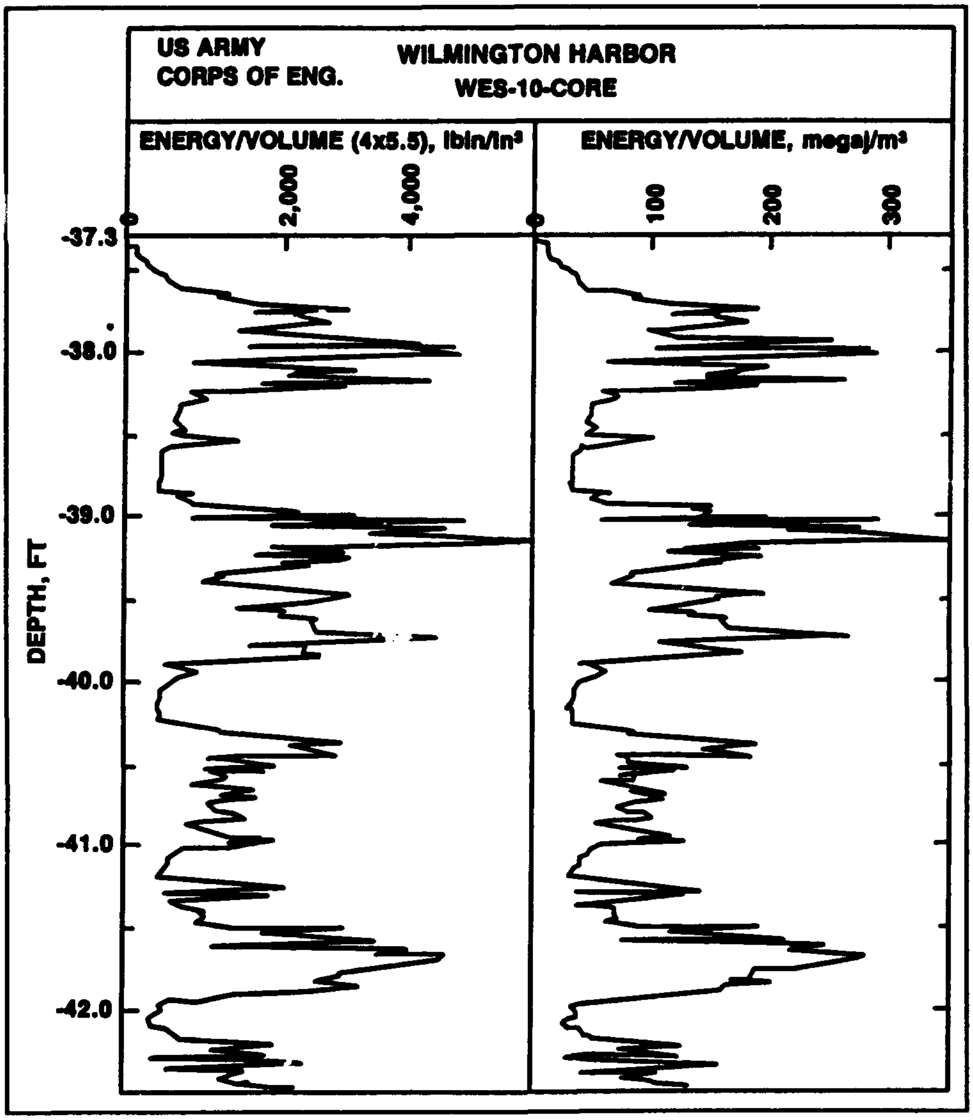

Figure 10. Combined-parameter estimate of specific energy of drilling from data shown in Figures 5 and 6

Drilling Parameter Correlations with Unconfined Compressive Strength

A subjective review of DPR records and rock core strengths from field sites indicated a good potential for correlation of drilling parameters with UCS.

Correlation of drilling parameters using rock core from field sites to establish basic relationships was not attempted because of the rapid variability of rock properties coupled with a relatively small number of UCS tests, typically about twenty at each field site. UCS test results are summarized in Chapter 3 and also given in the Point Load and Unconfined Compressive Strength (PLUCS) Data Base System (Smith 1992). The PLUCS is contained on the enclosed diskette. Intuitively obvious is that higher bit pressures should be required to drill higher strength materials and that lower advance rates would also be expected in the stronger materials. Also, available data from drilling rates in the mining and tunneling industries (Howarth and Rowlands 1987, Somerton 1959) indicate a correlation of drilling parameters (bit force, rotation rate, and advance rate) with UCS. The potential for field application of a correlation with UCS was considered good since UCS is an accepted measure of strength in the dredging community and since UCS correlations could be assessed immediately, unlike the correlation of specific energy of drilling with specific energy of excavation which must await actual rock dredging in order to be established. For these reasons, establishing a drilling parameter correlation with UCS became a goal of the work unit.

Somerton's index for resistance to drilling was first applied to DPR data from Wilmington Harbor to illustrate the possibility of such a correlation. Somerton's index is defined as

$$R_d = F\sqrt{\frac{\omega}{s}} \tag{3}$$

where R_d = Somerton's index for drilling resistance
F = bit force
ω = rotation rate
s = speed of advance

Figure 7 displays a combined-parameter estimate of UCS developed for illustrative purposes, based on Somerton's index to provide a correspondence of estimated UCS within the range of actual strengths of rock core tested over the site. While a general correspondence of this estimated UCS with actual strengths of rock core taken from some of the same positions in bore holes could be observed, rock strength at this site is highly variable so that a very large body of data would be required to establish a correlation with confidence. Variability of rock strengths is typical of coastal deposits and most other natural materials. For these reasons, selected uniform natural rock materials and several man-made rock simulants were used to obtain drilling parameter records for materials of known strengths.

A laboratory DPR drilling plan was formulated to obtain DPR records in uniform material of various strengths. Blocks of rock from two uniform natural formations, Berea sandstone and Indiana limestone, were placed in the ground at the WES to be drilled using the same drill rig and DPR system as was used at the

field sites. In order to obtain DPR records in a wide range of uniform materials, several different rock simulants were placed in 18-in. auger holes in lifts according to strength class. Rock simulants were produced in target strengths ranging from 300 psi to 10,000 psi, using water, portland cement, masonry sand and bentonite mixes in various proportions. Figure 11 shows diagrammatically the placement of these materials. There were actually five auger holes used plus two pits dug for placement of the limestone and sandstone, hereafter referred to as Pits 1 through 7. Five layers of common building bricks were placed below the limestone block. This ceramic material was used because of its availability and was placed only to see how well the DPR records would respond to jointed media, and no strength correlations were attempted. These materials were all drilled using an NX core bit to obtain drilling parameter records and core of each material strength for UCS testing. Although no provision was made for in situ saturation, these materials were placed in moist soil and remained in place for more than a month during a rainy period; and, during coring operations plain water was used for drilling fluid. Accordingly, after other laboratory preparation, the core was saturated. Immersed samples were towel-dried prior to UCS testing. The resulting data were used to determine a correlation over a wide strength range of the drilling parameters (bit force, rotation rate, and advance rate) with UCS, based on Somerton's index for resistance to drilling.

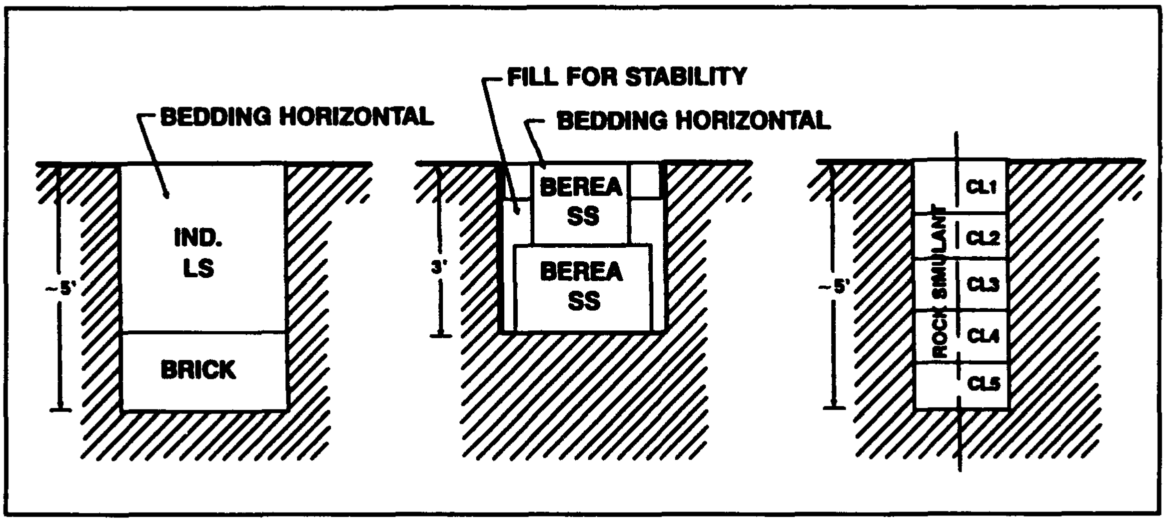

Figure 11. Rock and rock simulant setup for DPR laboratory drilling tests

Several problems with the DPR system occurred during the laboratory test drilling, some of which adversely influenced the acquisition of data. The pressure transducer for downthrust was inoperative during coring of rock simulants in Pit 1 and Pit 2, which involved a total of seven boreholes. Downthrust pressure and the weight of the drill head and drill string are used by the software along with pull-up pressure, to determine bit force. During drilling operations, downthrust varies little as virtually all variation in bit force is due to the driller's adjustments of pull-up. Accordingly, the downthrust channel had not been selected for monitoring in real time. Since downthrust varies little, bit force could easily be estimated with

reasonable accuracy if drilling in hard materials, but since these corings involved weak rock simulants, all DPR data from Pits 1 and 2 were rejected. The performance characteristics of this pressure transducer were not available such that an off-the-shelf replacement could be retrofitted, and an exact replacement was obtained from Solentanche, shipped from France. Although repair problems common to drill rigs had occurred on several occasions at field sites, no problem with the DPR system had surfaced throughout explorations at all four dredge sites, which involved exposure to saltwater environments. Another problem which resulted in poor data acquisition was rapid and erratic variations in recorded advance rates which were noticed on many DPR records. This drilling was done at higher rotation rates than the field work. Different drillers were used and rotation rates were left to their judgement as is usual practice. However, a whipping of the depth transducer control cable occurred during some of the drilling operations as a result of vibrations induced by the high rotations. The point of attachment of the cable was changed to eliminate this problem. Such problems pointed to the need for occasional alternate monitoring of all DPR channels.

The Enpasol software was programmed to compute Somerton's index as a function of bit force (lbf), rotation rate (rpm), and advance rate (ft/min), and averaged values of this computed parameter for each material strength class were correlated against average UCS tested for those same materials. Primarily because of the problems discussed above, the author rejected portions of, or entire holes of data. Mr. James B. Warriner, Rock Mechanics Branch, Geotechnical Laboratory, independently examined the DPR's graphical outputs and verified the rejection of data. To be accepted as useful DPR data, segments of both bit force and Somerton's index had to be smooth and constant on graphical display through a minimum depth interval of 0.1 ft on plots generated using the five-step data smoothing routine built into the software. Mr. Warriner also performed the resulting statistical analysis. Final results from the Enpasol software computation of Somerton's index for each material strength are described below. For each material class having sufficient data, the mean, standard deviation, and Chauvenet rejection criterion are given.

Class 1 material data were of good quality (as compared with the overall data set). An aggregate total of 6.6 ft of data produced a correlatable mean index of 6,503 with a standard deviation of 2,561. There was no justification for datum rejection within a probability of 1:132.

Class 2 material data were of acceptable quality and could be examined as a normal distribution. An aggregate total of 2.9 ft of data produced a correlatable mean index value of 2,499.3 with a standard deviation of 1,126.4. A total of 0.2 ft of data were rejected, leaving a probability of 1:58 that any values are not appropriate.

Class 3 material data were rejected during examination of the original DPR graphical data.

Class 4 material data were only of fair quality. Examination as a standard distribution was done. An aggregate total of 3.4 ft of data produced a mean value of 3,149.9 with a standard deviation of 1,717.7. The broad distribution and large relative standard deviation did not justify any rigorous data rejection. The most encouraging data set descriptor here was the probability of 1:68 that any used data are not appropriate.

Class 5 material data were rejected during examination of the original DPR graphical data.

Class 6 material data were poor because they consisted of only one measured interval in a single hole. It was relatively long (1.1 ft) and uniform (i.e., little variation in any of the drilling parameter values) but provided only the single correlation value. The data were used.

Class 7 material data were even poorer than the preceding because the single measured interval was shorter (0.4 ft). However, the data were used.

Class 8 material data were not considered good because of the wide variation of only three observed interval values, with an aggregate total of 3.0 ft of data. Rigorous data rejection criteria did not allow any improvement because of the wide separation of values and consequent uncertainty as to a valid mean value and standard deviation. The data were, nevertheless, used.

Limestone data were good and could be represented as a normal distribution. An aggregate total of 12.3 ft of data produced a correlatable mean index value of 26,380.2 with a standard deviation of 8,010.8. There was a probability of 1:246 that any retained data were not appropriate. There was no data rejection.

Berea sandstone data were also good. An aggregate total of 13.9 ft of data produced a mean index value of 19,061.7 with a standard deviation of 3,449.8. There was no data rejection within a probability of 1:278.

Results of UCS tests on the rock simulants and the natural rocks are shown in Table 1. These mean UCS values were paired with the mean Somerton's index values for each material class to determine a condensed data set consisting of eight averaged data sets. Figure 12 shows that data set graphically. Results of a linear regression are also shown. For this regression, there was no weighting done based on size or quality of the individual data sets. The resulting relationship to estimate UCS using drilling parameters may be expressed as

$$UCS = -486 + 0.368\, F \sqrt{\frac{\omega}{s}} \tag{4}$$

where UCS = unconfined compressive strength in psi
F = bit force in lbf
ω = rotation rate in rpm
s = advance rate in ft/min

Table 1
Results of Unconfined Compressive Strength Tests on Rock Simulants and Natural Rock Cored in Laboratory DPR Test Drilling

Material	No. of Tests	UCS, psi	Standard Deviation, psi
Class 1	1	341	--
Class 2	4	680.8	205.4
Class 3	3	1,050.0	69.7
Class 4	14	1,328.4	108.3
Class 5	2	3,151.5	103.9
Class 6	10	4,486.7	289.6
Class 7	11	1,0464.3	1,351.2
Class 8	7	1,810.3	115.6
Indiana limestone	30	9,375.3	497.9
Berea sandstone	16	7,283.6	703.46

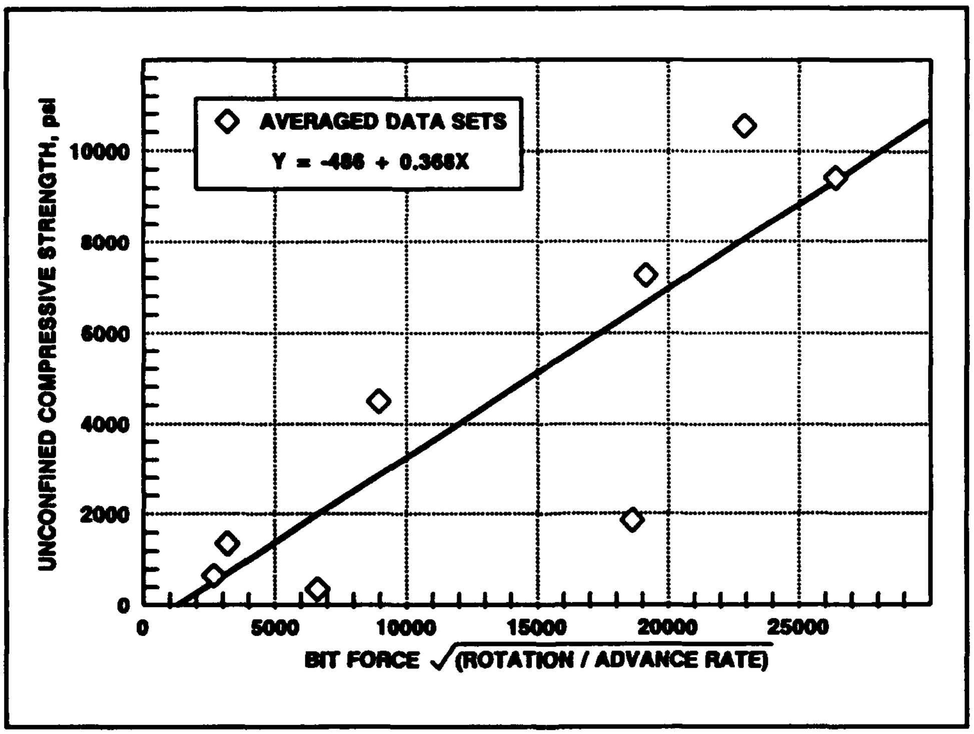

Figure 12. UCS correlation from DPR drilling tests

The resulting correlation coefficient was 0.84. The correlation obtained clearly demonstrates that drilling parameters can be correlated with UCS over a wide strength range involving weak rock. This correlation is conservative in that a better correlation could be obtained by eliminating data of lesser quality. The scatter of data here could be greatly reduced by not using the averaged data set for Class 8 material (1,810 psi) for which the corresponding DPR data were questionable as described above.

The above correlation was based on DPR records and UCS tests on materials having a wide range in strength — from about 300 psi to more than 10,000 psi. Better correlations can be obtained if based on fewer materials covering a smaller strength range. Figure 13 shows a DPR plot of a combined-parameter estimate of UCS for the Indiana limestone. Here, Somerton's index was not employed; the relationship used here was developed based only on DPR observations made in this one material and formulated to produce the known average strength value of 9,380 psi, as determined from standard UCS tests on the limestone core (see Table 1). Note that as the other drilling parameter values vary widely, the estimated UCS varies little, as would be expected in this uniform natural material. The relationship used here to estimate UCS is

$$UCS = 0.45 \frac{\omega}{s} \sqrt{F} \tag{5}$$

where variables are as previously defined.

Figure 14 shows a DPR plot of a combined-parameter estimate of UCS in the Berea sandstone using the same relationship developed for the limestone. Note that a lower strength is indicated which corresponds closely to the average strength of 7,280 psi with a standard deviation of 703 psi for the sandstone core tested. Although based on only two borings, this comparison serves to demonstrate that drilling parameters do follow UCS closely in these materials.

This comparison identifies the need for further drilling tests in these two uniform materials to obtain sufficient data for establishing a refined correlation with confidence.

The response of the DPR to jointed media can be seen on laboratory test drilling DPR records. The brick that was placed below the limestone block was encased in plywood and banded so that the entire pallet of brick could be lowered into place at the test site. Refer to Figure 13. Note the decreases in bit force and UCS, and an increase in speed as the plywood which separates the limestone and brick is encountered at 2.5 ft. Below this, the first three layers of brick can be clearly identified. In Figure 14 the close joint between the two quarry-sawn blocks of sandstone can be identified at mid-depth as a momentary increase in speed and a decrease in UCS.

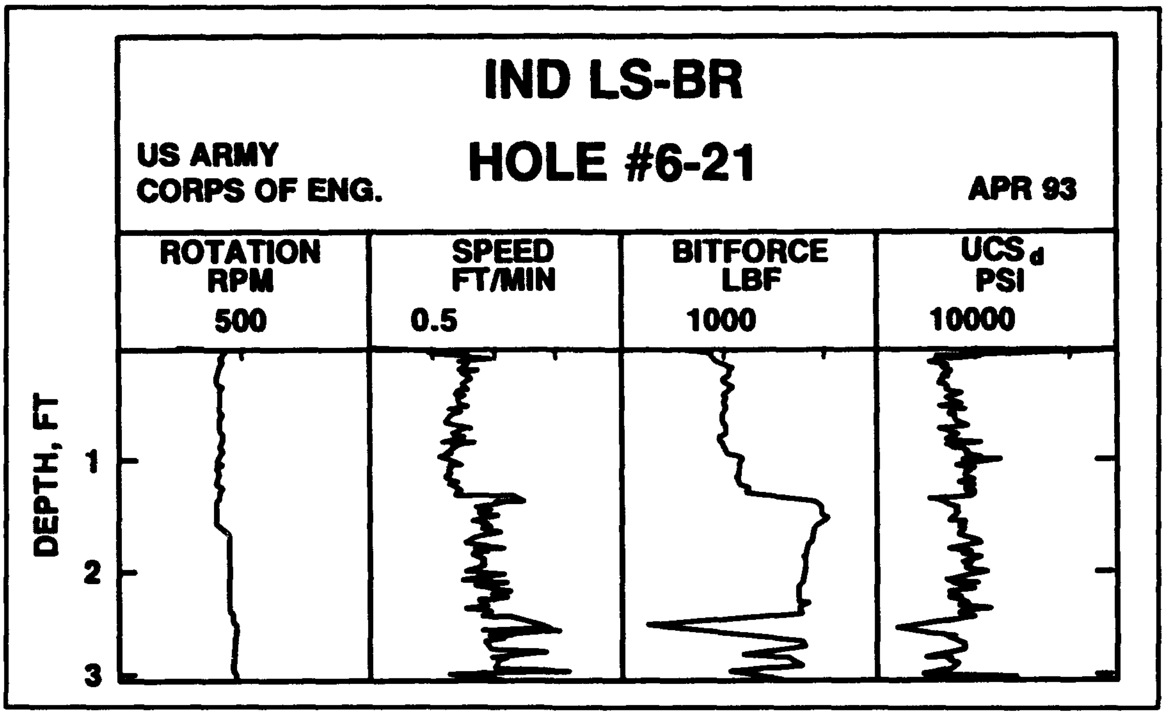

Figure 13. DPR drilling tests in Indiana limestone overlying brick

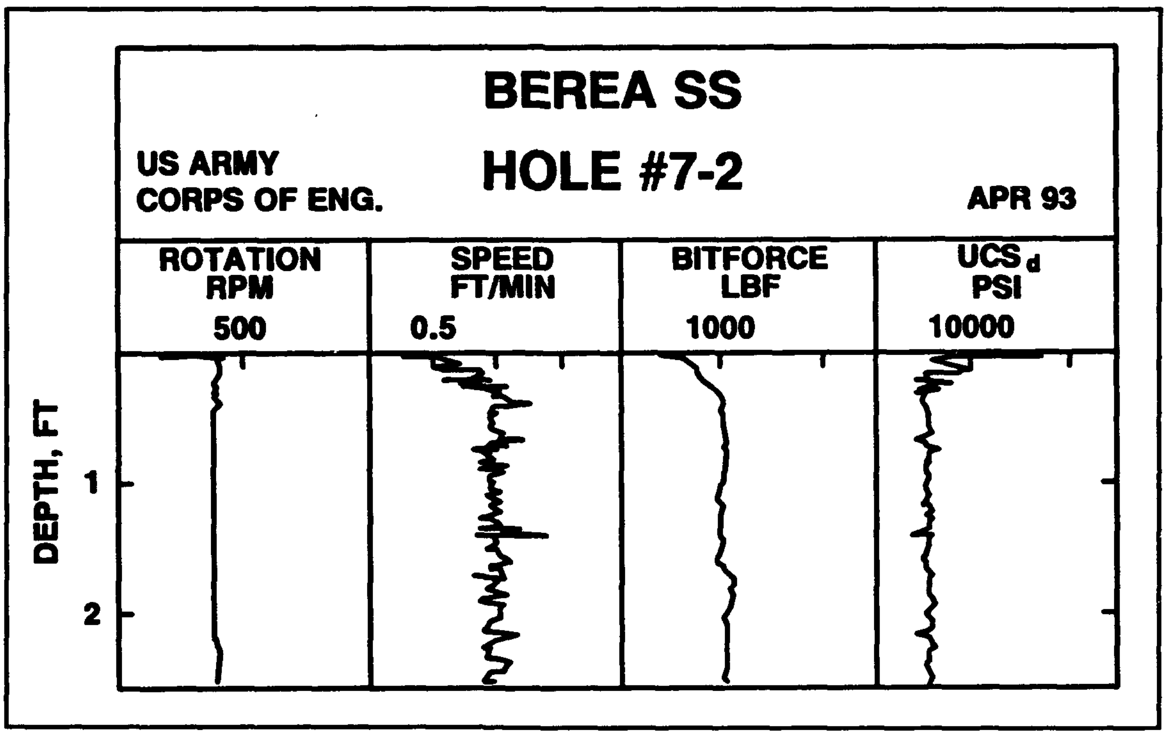

Figure 14. DPR drilling tests in Berea sandstone

3 Point Load Test as a Field Strength Index for Rock Dredging

The Point Load Test

The point load test was originally proposed (Broch and Franklin 1972) as a means of providing for destructive strength testing of hard rock materials with a portable apparatus, such that the tests produced a field strength index which could be correlated with UCS. Much of the costly laboratory testing requiring large, stationary machines could be avoided in exploration for rock site characterization. The point load test loading geometry produces a failure mode which closely approximates a tensile failure, and of course does correlate well with the uniaxial tensile or the Brazilian tensile test strength (Bieniawski 1975, Wijk 1980). Accordingly, correlation of point load strength with unconfined compressive strength could be expected to closely follow the tensile strength to unconfined compressive strength correlation for a given material. For this reason correlation of point load strength to UCS is material specific. For good estimates of UCS a good correlation must be possible between compressive and tensile strengths for the material in question.

Point Load Test Standards

A proposed standard for the point load test was published by WES in the Corps' *Rock Testing Handbook* (USAEWES 1982). This standard was based largely on Broch and Franklin (1972), supplemented with other works (Bieniawski 1975) and the WES experience. Subsequently the International Society for Rock Mechanics (ISRM) published a suggested method for determining point load strength (ISRM 1985). This ISRM standard was incorporated in the new *Rock Testing Handbook* (USAEWES 1989) as RTH Std 325-89, replacing the original *Rock Testing Handbook* standard. There were few significant changes in this new standard. One change recommended a reference or standard international size of 50 mm where data from size-dependent point load

tests on various-sized specimens were to be converted to one size, as is necessary when point load strengths are used for strength classification purposes. The American Society for Testing and Materials (ASTM) is presently considering a standard test method for determination of the point load strength index of rock. Although proposed ASTM standards may not be reproduced in part or quoted, the author has reviewed this proposed standard and opines that the finished version will be generally compatible with current USACE practices based on the earlier publications given above. The author has suggested that additional precautions and procedures be given for the testing of weak, saturated and/or vuggy rock often encountered in dredging applications. In the following abridged description of the point load tester and the point load index, the specific restrictions and definitions of terms given are consistent with the ISRM's "Suggested Method for Determining Point Load Strength," unless otherwise indicated.

The Point Load Tester

Point load tests are performed by loading the sample between two platens having 60-deg conical points with a 5-mm point radius. Thus, a sufficient point load can be provided to fail even hard igneous samples using a small portable test apparatus. A typical load capacity is 10,000 to 15,000 lb (USAEWES 1982), which is more than adequate to fail the higher strength rocks when testing NX-size (54-mm) core. The apparatus consists of an adjustable passive platen and an active platen providing the load through a hydraulic ram; pressure is provided by a second piston manually advanced by a mechanical screw with handle or by a manually operated reciprocating piston with check valve. A hydraulic pressure gauge records pressure at failure, and the gauge reading is multiplied by the area of the piston to give total point load, P, on the specimen. Different gauges can be used to produce accurate readings for both very high and very low point loads to accommodate a wide range of rock materials. More detailed requirements for test apparatus geometry, measuring provisions, and calibration are given in the Corps' *Rock Testing Handbook*, RTH Std 385-82 (USAEWES 1982), and in the ISRM's "Suggested Method for Determining Point Load Strength" (ISRM 1985), which has been incorporated in the new *Rock Testing Handbook* (USAEWES 1989).

A point load tester may be constructed using the criteria given in these publications, but several manufacturers of testing equipment now market point load testers. Both small hand-portable testers intended for field use and larger, more convenient to use, laboratory testing machines are available.

Point Load Index

Results of point load tests are usually expressed in terms of the point load strength index I_s which is, in accordance with the standards cited above, determined by dividing the total load P by D_e^2 where D_e is the equivalent diameter. The index for a given size core is directly related to the material's

tensile strength and can be correlated with UCS. Point load tests may be performed on core specimens without standard preparation or on a series of irregular rock fragments. Tests can be carried out using three different sample geometries, summarized below.

In the first sample geometry, tests on cylindrical core may be performed diametrically, in which case no preparation of ends is required. For this test, the nearest end point must be at least one radius away from the plane of loading. D_e is taken to be the distance between the loading platens or sample diameter.

In the second sample geometry, the core may be loaded axially. For the axial test the core ends must be sawn or split to produce a plane for the platens to bear upon; however, no accurate preparation is required, such as grinding of the ends. In this case, a length-diameter ratio ranging from 0.3 to 1.0 should be used, and I_s is computed using $D_e^2 = 4 A/\pi$ where A is equal to width times the distance of the minimum cross-sectional area of a plane through the loading platens. This test has the advantage that very short core pieces can be tested. This test also allows for testing in a perpendicular plane to that of the diametrical tests, which makes determination of strength anisotrophy easier than with the more usual unconfined compressive strength tests. Figure 15 shows an axial sample being positioned for testing in a point load tester and Figure 16 shows a typical failure after axial testing. Figures 17 and 18 show a diametrical sample under test and a typical diametrical failure. The core size shown here is NX (54-mm), about 2-1/8 in.

The third sampling geometry is the irregular lump test, which can be performed where no core is available in which case the square of equivalent diameter D_e^2 is computed as above; and D_e should be as close as possible to the site-size core diameter, especially where diametrical point load tests are also conducted. The irregular lump test is best performed using a width-to-length ratio between 0.3 and 1.0, preferably close to 1.0. In all of the above point load tests, ten or more samples should be tested for each material, more if the rock is not uniform.

When first introduced, point load strength was mainly used to predict UCS (Broch and Franklin 1972), which was the established test for general rock strength classification. UCS is certainly the only widely accepted strength criteria for dredging applications today. However, even when making correlations to obtain UCS, the I_s should be given. I_s is size dependent and should be correlated to a standard size when published. As given above, the international standard diameter is 50 mm. This index, written $I_{s(50)}$, is often used directly for hard rock classification. The NX core size (54 mm), which is often used in U.S. practice, is close to this size and correction to NX size is recommended especially where the site exploration used NX-sized core. This strength index would then be designated as $I_{s(NX)}$. Procedures for correcting as-taken I_s to a standard size are given in the Corps' *Rock Testing Handbook* (USAEWES 1982, 1989) but the testing of samples close to a standard size is recommended to minimize error.

Figure 15. Axial point load test

Figure 16. Typical axial point load sample after failure

Figure 17. Diametrical point load sample under test (ends were sawn but could be irregular)

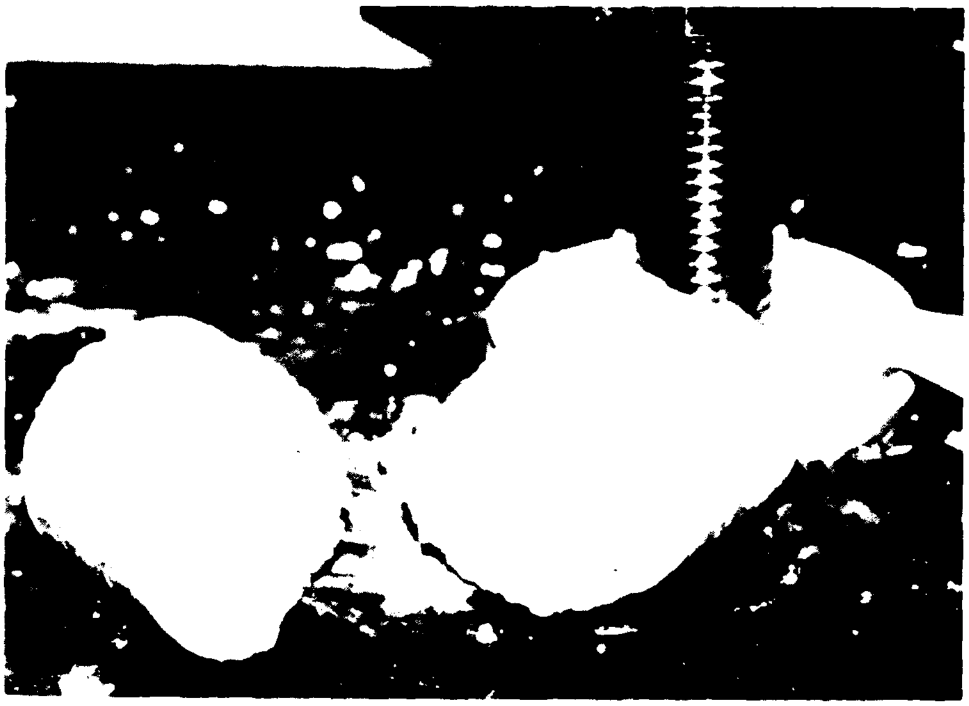

Figure 18. Typical diametrical point load sample after failure

Unconfined Compressive Strengths

Correlation of I_s with UCS is both material-specific and size-dependent. Therefore, for best accuracy this correlation should be established for each site-specific material. In this case, a number of UCS tests would be necessary; but even so, the time and cost saving for large numbers of strength tests would be significant using the point load tester. On the average, UCS is 20-25 times the point load strength ($I_{s(50)}$), but can vary over a much wider range (ISRM 1985). In reconnaissance exploration where site-specific correlations or other material-specific information is not available, the UCS can be estimated using a size correlation graph (Figure 19) to obtain the point load index to UCS conversion factors. For example, a conversion factor of approximately 24 is found if using the common NX (54-mm) core size.

Point load tests on igneous and the harder sedimentary rocks could be expected to have a reasonable correlation with UCS using the factors indicated. However, since these and similar results of others were developed based on hard rock data (Bieniawski 1975, Broch and Franklin 1972), such size correlation graphs provide no basis for use of point load test results for the weaker rock materials, which are typically dredged by mechanical means.

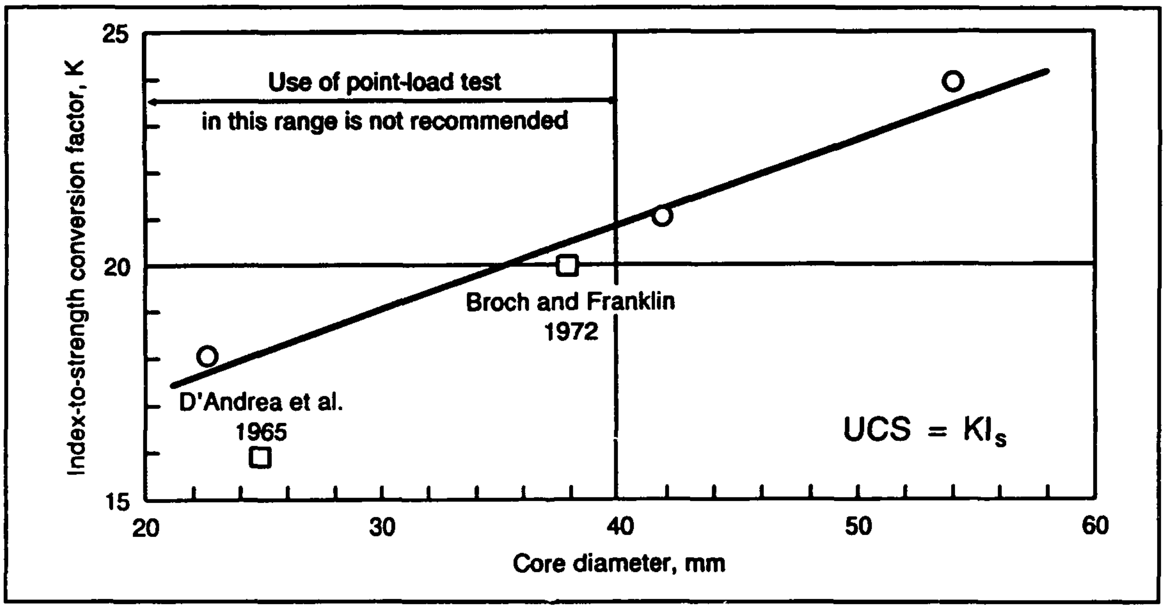

Figure 19. Size correlation graph for index-to-strength conversion (after Bieniawski (1975))

Comparative Testing Program

The primary purposes of this testing program were to demonstrate the applicability of the point load test method for weak, saturated dredged rock and to

determine any correlation with UCS. In accordance with these major purposes most testing was done on saturated samples; however, some testing of oven-dried sandstones and limestones was done to show wet versus dry strength comparisons.

Dredged material was obtained from core taken at DPR exploration sites at Wilmington Harbor, SC, Kings Bay, GA, and Grays Harbor, WA. (The DPR method and capabilities were described in "A Drilling Parameter Recorder for Rock Dredging Exploration," WEDA XIV (Smith 1993) and in Chapter 2 of this report.) Dredged material was also obtained from lump samples taken by divers at Port Everglades, FL, and a sample from Brunswick Harbor, GA, provided by USACE District Savannah. These dredged materials were each classified as a biohermal lime rock except for the silty sandstone from Grays Harbor. Because the dredged material was highly variable, uniform natural materials and a weak rock simulant were used to further establish relationships. Indiana limestone, the most uniform of the natural materials tested, was used to obtain both a wet versus dry strength comparison and an I_s to UCS correlation factor. Dardanelle and Ozark sandstones were tested using available NX-size core to show further wet versus dry strength comparisons. Berea sandstone was comparatively tested saturated to establish an I_s to UCS correlation factor for this very uniform rock of moderate strength.

Because the weaker natural rocks are more highly variable, a rock simulant was tested to provide an I_s to UCS correlation factor for very low strength material. This material was produced using a portland cement, masonry sand, and bentonite mix to obtain a target strength in the 600-psi range.

Rock core and dredged fragments from DPR field sites were transported in the water from those harbors in either sealed polyvinyl chloride (PVC) tubes or in open containers. Rock was kept immersed in water until tested, except for brief periods necessary for laboratory preparation. No attempt was made to verify percent saturation, although the author opines that the in situ rock most certainly contained some organic gases and that saturation was less than 100 percent. The other rock materials and the rock simulant were saturated by progressive immersion to avoid poorly saturated core centers due to entrapment of air. These samples and those from the field sites are referred to as having been tested wet; varying degrees of saturation are likely represented. Dry samples were oven dried until sample weight did not decrease on successive days. These samples were allowed to cool at ambient indoor relative humidity and temperature prior to testing.

Data Base System

A data base system was developed to store, retrieve and compare rock test data: the Point Load Index and Unconfined Compressive Strength (PLUCS) Data Base System (PLUCS). The PLUCS is an open-ended system, which presently contains data from over 400 rock tests from 10 different material sources. About three-fourths of these tests were performed on wet samples (see summary of data

contents, Table 2). In addition to displaying summary data from individual tests such as type test, sample dimensions, and breaking strength, the PLUCS system will, for a specified material and/or source location, scan the data base and compute average strengths, wet/dry strength ratios, and unconfined compressive strength versus point load index correlation factors. Most point load index tests in this data base were performed on NX-sized (54-mm) samples, a size commonly used by the U.S. Army Corps of Engineers. Since the point load index I_s is influenced by sample size, and correction to standard size must be made for strength comparison or rock classification purposes, the PLUCS software automatically corrects index values to NX size when data are entered so that all index values recorded in and displayed by the data base are $I_{s(NX)}$, although actual sample dimensions are stored.

Table 2.
Summary of Number and Types of Tests Contained in the PLUCS Data Base

Rock Material	W-Wet D-Dry	UCS	$I_{s(NX)}$
Wilmington Harbor lime rock	W	21	22
Kings Bay lime rock	W	21	12
Port Everglades lime rock	W D	15 3	13 3
Brunswick Harbor lime rock	W	1	1
Grays Harbor silty sandstone	D	1	12
Indiana limestone	W D	30 29	35 36
Dardanelle sandstone	W D	11 11	-- --
Ozark sandstone	W D	11 10	-- --
Berea sandstone	W	16	29
Rock simulant	W	32	31

The PLUCS Data Base System is a completely self-contained system that can be executed without additional software and can be executed on any IBM-compatible personal computer (PC). However, updating of this system does

require additional licensed software. The executable version of PLUCS has been published and updated through the USACE Dredging Research Program (Smith 1991, 1992). All data in PLUCS are given in English (Non-SI) units. A copy of the PLUCS Data Base System is included with this report.

Results and Observations

Comparison of averaged strength parameter values of UCS and $I_{s(NX)}$ for the biohermal lime rock from Port Everglades, Wilmington Harbor, and Kings Bay resulted in similar UCS to $I_{s(NX)}$ correlation factors for each of these sites, as shown in Table 3. Although these materials were highly variable as is indicated by the high standard deviations for each of the test sequences, correlation factors are consistently within a small range. The average correlation factor is 14.3, with a corresponding standard deviation of less than 7 percent. The apparent inconsistency may be explained by the way in which the samples were taken. Since the primary purpose of this test was to obtain a correlation factor for this variable material, and sufficient material was not available to obtain a large number of samples in each strength range at the sites, point load and unconfined compressive test samples were taken in sets from discrete small volumes of material. In the case of Point Everglades, core was taken for both types of tests from large rock fragments taken from the harbor bottom. Each intact fragment could reasonably be assumed to be much more uniform in strength than the material over the site. Core for both point load and unconfined compressive samples were taken from each fragment and although each sampling set was too small to infer a reliable correlation factor, all such data were lumped together in the data base from which could be computed a site-specific UCS to I_s correlation factor. The use of a correlation factor so derived makes the assumption that the correlation factor, being material-specific, would change little over the site within the same material, even though larger strength changes may occur.

Table 3. Comparison of Results from Unconfined Compressive and Point Load Testing for Biohermal Lime Rock

	UCS		$I_{s(NX)}$		K
Location	No. of Samples	mean* (psi)	No. of Samples	mean* (psi)	Correlation Factor
Wilmington Harbor	21	4,347 (3,191)	22	329 (210)	13.2
Kings Bay	21	3,436 (4,446)	12	232 (260)	14.8
Port Everglades	15	2,141 (1,080)	13	143 (108)	15

* Standard deviation shown in parentheses.

A similar bias relative to random sampling was accomplished for the rock from Kings Bay and Wilmington Harbor. Rock was taken in the field using a 4-in. core barrel. Although core recovery was often poor, many core pieces were long enough so that one 45-mm core for point load testing and two 35-mm cores sufficient for unconfined compressive testing could be taken parallel to the original core centerline. Core samples for all these tests were taken to maximize the number of samples from a limited amount of material. Accordingly, a perfect pairing of point load tests with unconfined compressive tests in adjacent material was not possible for all samples, as is evident from Table 2. However, the sampling and testing plan used, coupled with the consistent nature of the rock material, produced $I_{s(NX)}$ to UCS correlation factors consistent over the three sites.

Special Testing Procedures

Testing procedures used were consistent with the ISRM's "Suggested Method for Determining Point Load Strength" and the ASTM D2938-86 "Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens." However, some special additional precautions were needed in point load testing of some rocks.

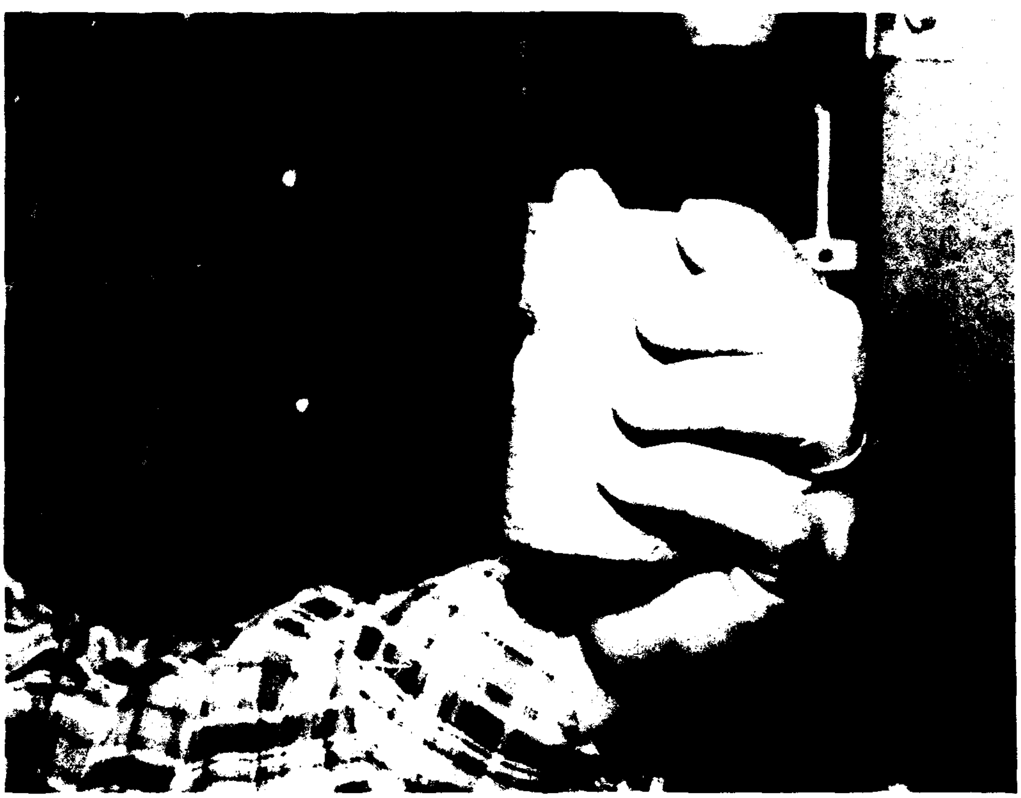

Figure 20. Core sample showing local crushing failure at the point load platens

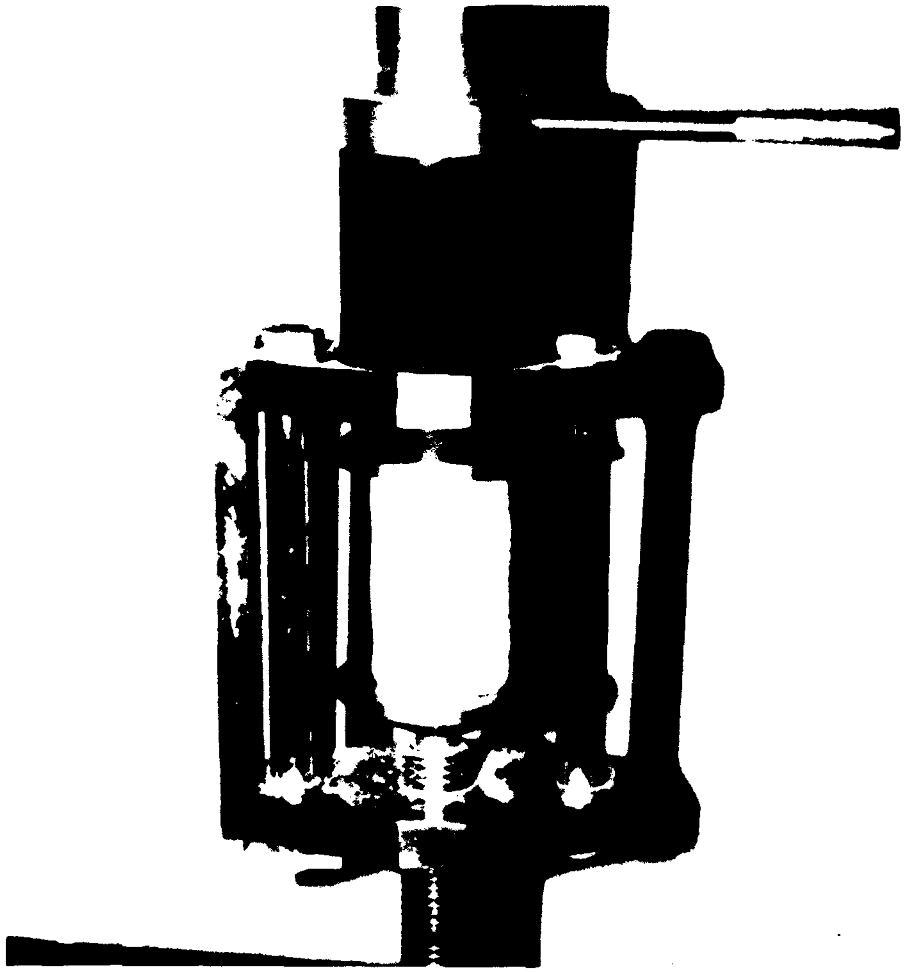

Figure 21. Flat platens pivoted on point load platens to load core in axial compression

Most of the biohermal lime rock, even though essentially isotropic, was either vuggy or had local inclusions of weaker material. In this case point load platens must bear on the harder portions of the nonuniform sample to produce the desired tensile loading of the overall cross section. Some coastal materials are weak but sufficiently brittle such that the point load platens can produce a local crushing failure and embed without failing the entire sample. A sample failed in this way is shown in Figure 20. Little of this material was encountered in the comparative testing program; however, in such a case, a valid point load test is not possible. Strength of such materials could, of course, be determined in laboratory UCS tests. However, a field strength test may be desired so that core can be tested in as-taken condition, to save laboratory costs, or for other reasons.

A field strength test on such friable rock is possible. Material encountered in the comparative testing program on which the platens produced local crushing was weak enough so that the entire cross section of core could be easily loaded in compression with a point load tester. Direct UCS tests have been successfully made on such material using flat platens configured to pivot on the point load platens. For material having UCS values of 2,500 psi or more, UCS can be determined in the NX size with a point load tester with alternative flat platens if it is capable of testing the harder igneous rocks in its normal point loading mode. The use of the point load tester for direct UCS tests in the field would require a small rock cutoff saw for sample preparation and would not meet all of the requirements for standard laboratory tests; however, results should reasonably be as consistent as point load strengths and are quite suitable for a field-determined strength index.

To demonstrate this technique a test was performed as shown in Figure 21. Test results were entered in the PLUCS data base as an unconfined compressive test, identified with "FL" after the sample number. This rock was from Port Everglades.

Point Load Index Strength Correlation to Unconfined Compressive Strength for Dredged Materials

The average correlation factor for the three lime rock sites discussed above was 14.3, which is low compared with an expected value of 24 based on hard rock testing experience. Because weak rock materials are by nature nonuniform in strength, the rock simulant was used to further show that consistent point load test results could be obtained for very weak saturated materials and to obtain a correlation factor for a material in this strength range. A total of 32 unconfined compressive tests on this material resulted in an average UCS of 626 psi, with a standard deviation of only 9.3 percent. A total of 31 point load tests were performed resulting in an average $I_{s(NX)}$ of 73.5 with a standard deviation of 16 percent. The corresponding I_s to UCS correlation factor is 8.5. The lowest correlation factor found for a natural rock site was 13.2; however, that was for material of much higher strength and of a different type. Certainly, site-specific correlation factors for weak, saturated materials can easily be one-half or less of published values for hard rock.

Comparative tests on Berea sandstone and Indiana limestone, both selected for their uniformity, resulted in $I_{s(NX)}$ to UCS correlation factors consistent with hard rock testing experience as shown in Table 4. These tests were performed using the same procedures and test equipment as those for the weaker materials, except as noted above under "Special Testing Procedures" (page 37).

Table 4.
Comparison of Results From Unconfined Compressive and Point Load Testing for Selected Sandstone and Limestone

Material	UCS		$I_{s(NX)}$		K
	No. of Samples	mean* (psi)	No. of Samples	mean* (psi)	Correlation Factor
Berea sandstone, W	16	7,284 (703)	29	313 (26.9)	23.3
Indiana limestone, W	30	9,375 (498)	35	408 (98.4)	23.0
Indiana limestone, D	29	11,780 (987)	36	433 (94.6)	27.2

* Standard deviation shown in parentheses.

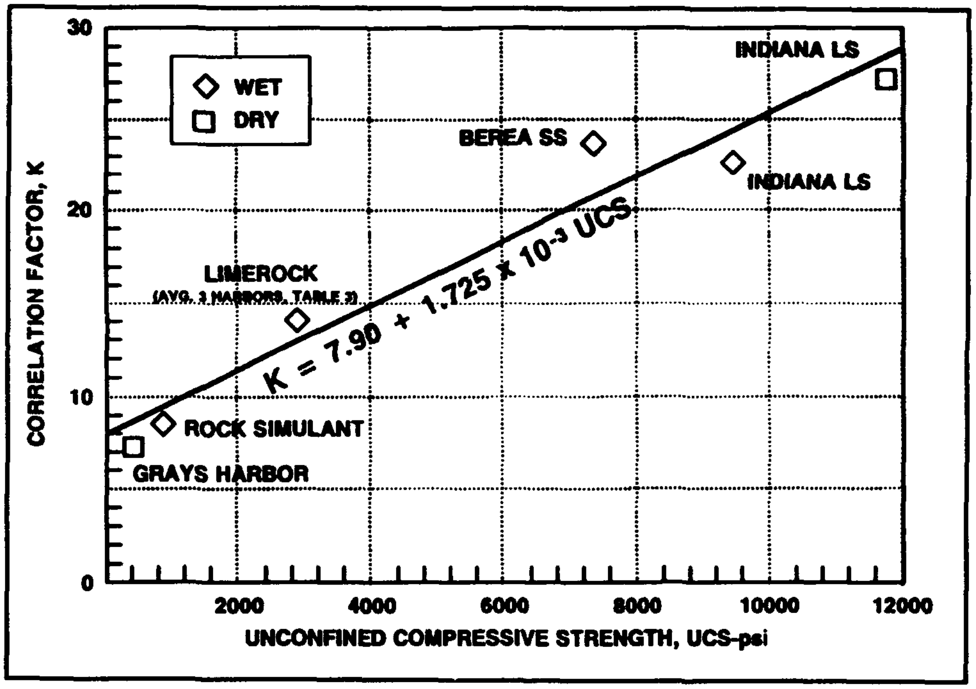

Figure 22. Variations of UCS to $I_{s(NX)}$ correlation factor for low strength rock

Review of the data discussed and displayed above and other data from the PLUCS showed a consistent trend toward lower correlation factors for materials of lower strength. The PLUCS was used to compute a correlation factor for materials for which both $I_{s(NX)}$ and UCS were available. Average UCS for each material type was plotted against those correlation factors as shown in Figure 22. Although

shown in the PLUCS content summary (Table 1), data from Brunswick Harbor were not used because only one test of each type was performed. However, data from Grays Harbor were used since several point load tests were performed and the material showed good uniformity for a weak natural material with a standard deviation in strength of 31.9 percent. Standard deviations for the other averaged data sets are given above. The author opines that additional data are needed to further establish the relationship between rock strength and the correlation factor. However, the linear fit shown is sufficient to demonstrate clearly that site-specific or material-specific correlation factors are lower for weaker rock, and that correlation factors in the neighborhood of 10 could be encountered in the very weakest rocks.

4 Conclusions and Recommendations

The capabilities of the DPR system as a site characterization tool for dredging have been demonstrated. The system has been successfully used for subaqueous drilling at four field sites and also in laboratory test drilling involving a wide range of material strengths. At the field sites the jack-up barge proved best suited to DPR exploration as it provides a very stable, yet mobile drilling platform even under adverse conditions. However, successful records of drilling parameters were obtained using both anchor and spud barges. A correlation with drilling parameters to obtain estimated UCS over a wide range of strengths has been determined, and the potential for better correlated relationships over a smaller strength range has been indicated by the drilling parameter to UCS correlation in Indiana limestone and Berea sandstone. A good potential exists for refining DPR correlations to estimate UCS as DPR systems are used at future field sites and as additional laboratory tests are analyzed. Also, general DPR operational techniques may be further refined as field explorations are carried out in other geologies.

Currently available methods of DPR application include the roller bit drilling of most holes, using the drilling parameters to provide site-specific correlations with a number of cored holes. This method allows for more boreholes at a site for the same cost since roller bit drilling is faster and requires no casing. This approach is particularly valuable when rock materials are highly variable with depth and over the site area. When core is taken in coastal deposits, core recovery is typically poor. In this case, the DPR records can easily show where in the core run material was recovered; and geological contact elevations can be determined with certainty even when no core is recovered. To infer in situ strengths from drilling parameters, the application approach recommended is to estimate UCS based on a site-specific correlation, since better results were demonstrated over a smaller strength range in the laboratory DPR drilling tests and since the relationship between strength parameters is sometimes material specific, as was demonstrated by the comparative testing program. Somerton's index of drilling resistance has been demonstrated to provide a reasonable drilling parameter correlation with UCS for both weak and high strength rock.

The point load test has been shown to be useful for weak, saturated rocks which are typical of many coastal deposits. Consistent, repeatable test results as well as correlation with unconfined compressive strengths have been shown.

Point load index to unconfined compressive strength correlation factors are low for such materials. Applicable established testing procedures should be followed (USAEWES 1989, ISRM 1985) with special additional precautions/procedures in the case of vuggy or weak and friable rock.

For correlations of I_s to UCS, a site-specific correlation factor should be developed if possible; but, if not, a material-specific correlation factor should be used, such as is available in PLUCS for several rock materials. The use of published average correlation factors based on hard rock testing should be employed only for very rough approximations or to assess relative strengths in the field, since results could be in error by a factor of two or more as has been shown for some weak, saturated rock.

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13. ABSTRACT *(Maximum 200 words)*

Two technologies are further developed to improve site characterization for rock dredging. A system for recording and analyzing the operational parameters of an exploration drill rig is described. Observed drilling parameters can be correlated with site conditions. The basic system, involving proven concepts and applications for land surface use, has been demonstrated in subaqueous applications at several dredge sites. The interpretive techniques that have been developed involve site-specific correlations and calculated combined-parameter estimates of in situ conditions, such as estimates of unconfined compressive strength. The point load test was originally intended for testing of hard rock materials to obtain a field strength index. To support the dredging use of the point load test, a comparative testing program was conducted, involving point load and unconfined compressive strength tests. Applicability of the point load test is shown for weak rock materials typical of many coastal deposits, and a correlation with unconfined compressive strength is demonstrated for several dredge sites, but indicating correlation factors much lower than those used for hard rock tunneling and mining applications.

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